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# **REVIEW AND EVALUATION OF THERMAL SENSORS FOR USE IN TESTING FIREFIGHTERS PROTECTIVE CLOTHING**

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**Roger L. Barker, Hechmi Hamouda,  
Itzhak Shalev and Jason Johnson**

**North Carolina State University  
Center for Research on Textile  
Protection and Comfort  
College of Textiles  
Raleigh, NC 27695-8301**



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# **REVIEW AND EVALUATION OF THERMAL SENSORS FOR USE IN TESTING FIREFIGHTERS PROTECTIVE CLOTHING**

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**Prepared for**

**U.S. Department of Commerce  
Building and Fire Research Laboratory  
National Institute of Standards and Technology  
Gaithersburg, MD 20899**

**By**

**Roger L. Barker, Hechmi Hamouda,  
Itzhak Shalev and Jason Johnson**

**North Carolina State University  
Center for Research on Textile  
Protection and Comfort  
College of Textiles  
Raleigh, NC 27695-8301**

**Annual Report**

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### **Notice**

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Annual Report

On

**Review and Evaluation of Thermal Sensors  
For Use in  
Testing Firefighters Protective Clothing**

Submitted to

**National Institute of Standards and Technology**

By

**Center for Research on Textile Protection and Comfort**  
College of Textiles  
North Carolina State University  
Raleigh, NC 27695-8301

**Jason Johnson**  
Graduate Student

**Dr. Roger L. Barker**  
**Dr. Hechmi Hamouda**  
**Dr. Itzhak Shalev**  
Principal Investigators

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## Overview

The Center for Research on Textile Protection and Comfort (T-PACC) at North Carolina State University is conducting a project which has, as its primary objective, the selection and evaluation of sensors that can be used to measure heat transferred through firefighter protective clothing materials, with the ultimate goal of applying this knowledge base to the development of fire scene specific sensor technology. The purpose of this annual report is to summarize progress made to date on this project, and to describe future work that will lead to the successful completion of the technical objectives set for the program.

## Summary of Progress

Significant progress has been made toward accomplishing the goals set for the first year of the program. The accomplishments made to date can be summarized as follows:

A review of state-of-the-art thermal sensor technologies has led to the identification and selection of four different sensors that are currently used for evaluating materials for firefighting applications. Each of the candidate sensors has been tested and comparatively evaluated based on a reasonably developed set of performance requirements for thermal sensors used for materials testing, or for thermal measurements in firefighting environments. Laboratory experiments have been conducted to characterize sensor response to different levels of nude and covered heat exposure and to evaluate the accuracy of the thermal measurements. Also, a burn model has been developed to determine tolerance times for each exposure condition.

Instrument studies have successfully identified critical differences in sensor performance that is providing a useful basis for selecting the optimum sensor for this application. Based on preliminary test results, the evaluation has been narrowed to four specific sensor technologies including a new small, lightweight sensor developed at T-PACC. Conclusions from this study are being implemented in conceptual design of a new generation sensor that is tailored to applications in structural firefighting hazard evaluation.

## Introduction

In many industrial settings, workers face potential exposure to fire hazards. This is especially true for fire fighters who may be exposed to many different thermal environments including severe flashover conditions. Exposure may result in skin burns or loss of life. Investigations show that fire fighters can be exposed to intense heat flux levels as high as  $40\text{kW/m}^2$  for relatively short periods of time [10]. Much work has gone into the characterization of the thermal environments experienced by firefighters [13]. Although protective clothing is available, quantitative evaluation of such clothing has typically been through small scale thermal protective performance tests (TPP) which measure heat transmission to the skin. With the use of thermal heat flux sensors, these tests give useful information about thermal protection [5].

An interest in sensor technology lies with the ability to predict burn damage levels that human skin would incur if a live subject had been exposed to similar conditions. Currently, a test procedure and facility exist on the campus of North Carolina State University at the College of Textiles for the purpose of assessing the extent and severity of human skin burn damage. The facility was designed to expose a clothed human mannequin to flash fire conditions. The potential skin burn damage can be evaluated using computer models when the local heat flux to the "skin" surface is known. The local heat flux is measured by 122 sensors mounted on the mannequin's surface. By varying the heat flux and exposure time, different accident scenarios can be simulated [11]. The information that these sensors provide is very useful in assessing a garment's overall effectiveness at protecting a person from serious burns or death during a flash fire exposure. There is, however, a broad range of thermal injury that may be sustained by firefighters [14]. For this reason, it is important that accurate measurements of heat flux be obtained at a variety of heat flux levels.

To date, no well documented review of the types and uses of skin simulant thermal sensors is available. This research attempts to evaluate the thermal sensors that have been used in the past and that are currently under development and provide such a review. One outcome of this research will be in the form of a recommendation for sensors to be used in laboratory fire experiments and fire experiments in the field. The purpose of this report is to summarize progress made on phases of the project focused on sensor technology and selection, and to present the results of laboratory tests designed to compare instrumented response to heat exposure.

Physiological burn damage rate models are based on knowledge of the intensity and duration of incident heat flux on the skin surface. Precise detection of surface heat flux incident level is, therefore, a key factor in calculating the burn damage predictions. The value of heat flux is dependent on the nature of the heat source but also upon both the thermal conductivity and surface temperature of the sensor, therefore, selection of a transducer is important. A sensor of inappropriate design may provide misleading results [11]. To evaluate the capabilities and limitations of different sensor technologies, an analysis of engineering design specifications must be made.

In order for the heat flux measuring devices to be analyzed, a list of performance requirements was prepared. The list was subdivided into two categories—application requirements and instrument requirements. To offer a better understanding , a description of the requirements is outlined below:

### **Performance Requirements**

#### **Application Requirements**

The potential applications for the thermal sensor include use in bench-scale tests of the thermal protective performance (TPP) test of firefighter clothing materials, use in instrumented manikin (PyroMan type) tests, and use as an instrument to characterize full scale or field exposures to structural firefighting environments. In light of potential applications a reasonable set of requirements follows:

- The thermal sensor should be small and lightweight. It should be rugged and sufficiently durable to withstand repeated exposures in laboratory tests of firefighter clothing materials or for use in full scale field evaluations of firefighter thermal exposures.
- For applications in testing firefighter clothing materials and thermal exposures, the sensor must be capable of accurately and reliably measuring both convective and radiant heat flux in an operating range of 0 to 2.5 cal/cm<sup>2</sup> sec (105 kW/m<sup>2</sup>).
- The thermal sensor must produce an output that can be unequivocally translated by an acceptable skin burn damage model. The translation from instrument response to predict skin burn injury should not require baseline calibration and an initial rate of temperature rise measurement.
- The optimal sensor should feature a design concept that can be easily and reliably manufactured in quantity with acceptable production economy.

### Instrument Requirements

- The thermal sensor must provide a rapid response for proper data acquisition. Rapid response is an important consideration contributing to enhance the value of the heat flux measurement for use in predicting the level of skin burn damage.
- The sensitivity of the thermal sensor must be such that it can detect heat flux in the lowest operating range with only slight variation due to heat leakage or thermal storage within the sensor. The sensor must output a strong and clean signal in such a manner that is immune from noise produced by extraneous electromagnetic interference.
- The sensor design should minimize storage of thermal energy that can occur in repetitive heat exposures. Heat storage is undesirable since it contributes to inaccuracy in the thermal measurement, especially at high heat flux levels.
- The sensor should have minimum impact on the thermal history of the overlaying materials through heat sink or temperature gradient effects.

### Sensor Selection

A review of state-of-the-art surface heat flux measuring devices confirmed the existence of a variety of sensor options, including devices that utilize buried thermocouple transducers, slug or heat capacitance calorimeters, thin foil or Gardon transducers, wafer type thermocouple transducers and suspended disk thermocouple transducers [1, 2, 3, and 4]. Based on stated applications, instrumental needs, and preliminary test results, four different thermal sensors have been selected for comparative testing and evaluation by this program (Table 1). Due to the reliability and long experience with the TPP benchtop testing, the TPP copper calorimeter sensor was chosen to act as a benchmark for the comparison of three selected sensors. The

following is a brief description of selected sensors.

### TPP Sensor

The TPP sensor is widely used in bench-top tests of thermally protective clothing materials. It is noted for rugged reliability and is a well-established sensing device for these applications. The thermal sensor itself consists of a copper disk 4 cm in diameter and 0.16 cm thick.

The thickness was chosen so that the temperature rise of the sensor approximates the temperature rise of human tissue when exposed to the same heat flux. It can be seen in the following equations, that the thickness of the sensor determines the mass of the copper, which determines the temperature rise with a given heat transfer:

Where:

$q$  = Heat Flux

$$q = \frac{MC_p\Delta T}{A\Delta t}$$

$M$  = Mass

$C_p$  = Specific Heat

$A$  = Area

$\Delta T$  = Temperature rise

$\Delta t$  = Time step

Mass can then be written as the following:

$$M=Ab\rho$$

Where:

$b$  = thickness

$\rho$  = density

The flux equation can then be rewritten by substituting the product  $Ab\rho$ :

$$q = \frac{b\rho C_p \Delta T}{\Delta t}$$

Since  $\rho$  and  $C_p$  are constants and  $A$  cancels out,  $\Delta T/\Delta t$  is directly only dependent upon the thickness. Based on pioneering work that was done by the military at Fort Rucker, Alabama, it was determined that a temperature rise in the skin surface of a pig of about 35°F resulted in 3<sup>rd</sup> degree burns. Therefore, it was calculated that with a sensor thickness of 0.16cm, a similar temperature rise could be attained under identical exposure conditions. This is important, since the sensor must represent the skin during an exposure in order to maintain the same temperature differences between the exposure source and the receiver, in this case the sensor.

The diameter was chosen to monitor a fairly large sample area of the test specimen; thus,

evening out construction variations in the sample. The diameter was also chosen to give a good average for the heat transmitted through the interstices in the fabric made by the intersection of yarns. However, it was designed smaller than the sample area to prevent any cooling effect from the specimen holder. The entire disk is mounted in an insulating block.

Four J-type (iron-constantan) thermocouples are secured in the disk, positioned at 120-degree intervals and at the center. This is to average out any variation in the temperature of the copper. The thermocouples are wired in parallel so that the voltage is the average of all four. The positions of the thermocouples were chosen to uniformly cover the sensor area.

The thermocouples are made from 30-gage wire, which is large enough to work with and small enough to minimize heat loss to the leads. The thermocouples are wired to a heavier gauge lead wire, which comes out of the back of the insulating block. The calorimeter face is also blackened to give it emissivity characteristics that approximate that of human skin.

#### Insulated Copper Sensor

The insulated copper sensor was developed at the Center for Research on Textile Protection and Comfort (T-PACC) at NCSU for use in the PyroMan fire test manikin. The insulated copper sensor consists of a thin copper disk, 1.27 cm in diameter and 0.15 cm thick, surrounded radially by a thin copper ring thermal guard. Both the disk and the ring are supported by an insulating holder to minimize heat transfer to and from the body of the calorimeter thus approximating one-dimensional heat flow [2]. Beneath the surface of the copper disk, an insulating air cavity is maintained and a T-type (copper-constantan) thermocouple is attached to the lower side of the disk [11]. The whole assembly is encapsulated within a protective shell.

The primary attributes to this design are its simplicity, small size and ease of operation. It is fairly rugged and possesses material properties that can be easily measured and controlled.

A thermal energy balance during the period of initial linear temperature responses can be stated as follows: The energy received by the front face of the calorimeter is equal to the energy conducted axially into the slug or

$$q_c = \rho C_p I (\Delta T / \Delta \tau) = (MC_p/A)(\Delta T / \Delta \tau) \quad (1)$$

In order to determine the steady-state heat transfer rate with this type of sensor, equation 1 must be solved using the known properties of the copper slug [2]. However, it is not possible to have a perfect insulator in practice. Some energy is transferred to and from the copper disk and the insulator and losses occur. These losses may be estimated as

$$\text{Losses} = K_l(T(t) - T_i) \quad (2)$$

where  $T_i$  is the initial temperature and  $K_l$  is an aggregate contact conductance between the copper disk and the insulator [3]. The calculation for heat flux, assuming losses, is detailed in Appendix A.

The thermocouple was attached to the insulated copper disk in accordance with the procedures outlined in ASTM D4108-87. As described by Grimes, a 0.0469 inch diameter (1.19 mm) hole is drilled into the rear surface of the copper disk. The hole is 0.040 inches deep (1.02 mm) and has a flat base where two leads of a 30 gauge T-Type copper/constantan thermocouple wire is inserted and secured in place by an 18 gauge copper plug. This allows for an intimate contact between the copper disk and the thermocouple due to the pressure exerted by the 18 gauge wire. After proper attachment, an 1/8 inch (3.18 mm) length of heat shrunk tubing is applied to the remaining length of the thermocouple wire, serving as a protection to the wires. To secure the thermocouple wire, the assembly is fed through a strain relief tube which is mounted into the insulating disk holder [3].

The copper disk and ring are secured within the disk holder by three retaining pins. The pins are inserted through 0.062 inch diameter (1.57 mm) holes in the insulating holder and the copper ring. The pins are located 120 degrees apart, perpendicular to the central axis and 0.040 inches (1.02 mm) back from the front surface. The retaining pins are seated into 0.030 inch diameter (0.76 mm) by 0.015 inch deep (0.38 mm) conical notches in the surface of the disk, minimizing the contact surface between the two and reducing the amount of heat loss from the copper disk [3].

The completed structure is then inserted and secured with a # 10-32 nut, lock washer, strain relief washer and nut into a cavity in the shell. The front surface of the transducer is then painted with a 0.0010 to 0.0015 inch (0.025-0.038 mm) layer of low gloss, high temperature black enamel paint. This is done to protect the surface and raise its diffuse emissivity to a value close to 1.0. The shell cavity protects the insulating holder and secures the copper disk in place. The shell is made from the same skin simulant thermoset plastic as the Embedded Thermocouple Sensor.

#### Embedded Thermocouple Sensor

This sensor is a thin-skin calorimeter that employs a Type T thermocouple buried below the exposed surface of a cast resin plug at a depth of 0.127 mm (0.005 in). The sensor is designed with a thickness greater than 0.25 inch such that backwall temperature conditions will not affect the response of the surface measurements. This means, that the sensor, for the exposure durations considered, is effectively of infinite thickness (infinite slab geometry).

The sensor is made of a thermoset polymer molded into a small solid cylindrically shaped plug. The polymer used, reportedly, exhibits a thermal inertia, ( $k\rho C_p$ ), similar to that of undamaged human skin [3]. The exact location (depth) of the thermocouple bead is critical in the accuracy of the calculated heat flux, and the predicted skin burn damage since clinical severity of burn damage is a function of the depth of skin destruction.

#### Surface Mounted Thermocouple Sensor

The device is a skin simulant heat flux sensor made of colorceran, a mixture of inorganic materials including calcium, aluminum, and silicate with asbestos fibers and a binder. The material thermal and physical properties are such that the heat transfer within it will be similar to that in human skin under a suddenly applied heat flux. While the individual properties are not a perfect match with those of the epidermis and dermis layers, the thermal

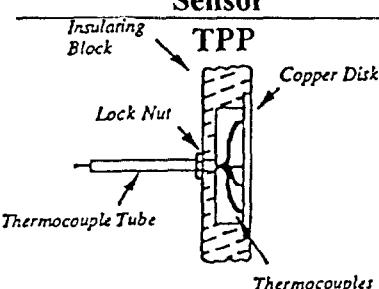
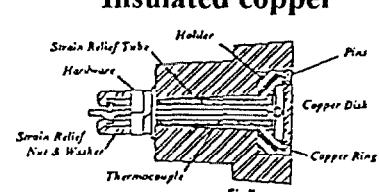
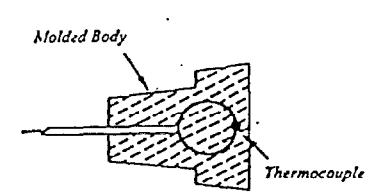
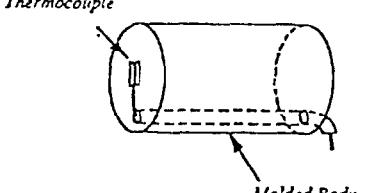
inertia, or its square root, the thermal absorptivity, are closely matched [4]. These properties are listed in Appendix A as they were taken from the literature.

A T-type (copper-constantan) thermocouple junction is mounted on the surface of the sensor. A hole is drilled along the length axis of the sensor to allow the thermocouple wire to be run up inside of the sensor. The thermocouple wires are held on the surface with a high temperature epoxy-phenolic adhesive. This adhesive has a short term maximum working temperature of 370 °C. This allows the sensor to be used in short duration flash fires [12].

The sensor has a length of 32 mm and a diameter of 19 mm. The length of the sensor was chosen for convenience, because the colorceron comes in 32 mm thick slabs. The diameter was selected to give a large enough surface area so that sufficient lead length could be given to the thermocouple on the surface to help eliminate conduction heat transfer effects to the junction [12].

Table 1 summarizes the salient properties of the sensors tested.

**Table 1. Thermal Sensors**

Sensor	Specifications*	Advantages/ Disadvantages
 <p><b>Copper Slug Calorimeter</b>  <math>d_s = 4.0 \text{ cm}</math>, <math>L = 0.16 \text{ cm}</math>  <math>d = 4.0 \text{ cm}</math>, <math>b = 0.16 \text{ cm}</math>  <math>m = 17.89 \text{ g}</math>  Four J-type Thermocouples</p>		<ul style="list-style-type: none"> <li>Adequate response time</li> <li>Durable</li> <li>Accurate measure of flux</li> <li>Unknown heat leakage</li> <li>Withstands long exposures</li> <li>Small deviation</li> </ul>
 <p><b>Insulated copper</b>  Copper Slug Calorimeter  <math>d_s = 2.63 \text{ cm}</math>, <math>L = 2.66 \text{ cm}</math>  <math>d = 1.27 \text{ cm}</math>, <math>b = 0.15 \text{ cm}</math>  <math>m = 1.31 \text{ g}</math>  One T-type Thermocouple</p>		<ul style="list-style-type: none"> <li>Adequate response time</li> <li>Durable</li> <li>Accurate measure of flux</li> <li>Known heat leakage</li> <li>Withstands long exposures</li> <li>Small deviation</li> </ul>
 <p><b>Embedded Thermocouple</b>  Thin-skin calorimeter  Buried thermocouple in thermoset polymer  <math>d_s = 2.6 \text{ cm}</math>, <math>L = 2.7 \text{ cm}</math>  One T-type Thermocouple</p>		<ul style="list-style-type: none"> <li>Fast response time</li> <li>Limited durability</li> <li>Small deviation</li> <li>Errors due to inaccurate thermocouple bead location</li> <li>Polymer cracks with repetitive exposures</li> </ul>
 <p><b>Surface Thermocouple</b>  Slug-type sensor  Surface thermocouple on colorceran body  <math>d_s = 1.9 \text{ cm}</math>, <math>L = 3.2 \text{ cm}</math>  One T-type Thermocouple</p>		<ul style="list-style-type: none"> <li>Fast response time</li> <li>Limited durability</li> <li>Accurate measurement</li> <li>Small deviation</li> <li>Cannot withstand long exposure at high heat flux</li> <li>Exposed thermocouple</li> </ul>

\* $d_s$  = diameter of calorimeter

$L$  = length of calorimeter

$d$ ,  $b$ ,  $m$  = diameter, thickness and mass of the copper disk in slug-type calorimeters.

## Application Conditions

In order to select appropriate test methods and specifications, the conditions under which protective clothing will be used must be considered. However, it is quite difficult to completely define the firefighter environment. This is because of the many environmental, physical, physiological and psychological factors that effect a firefighter's interaction with the fire scene. Nonetheless, data has been collected and information is available to provide a range of common thermal environment conditions that are classified into three general categories. These classifications are identified as Routine, Hazardous and Critical, and are described in detail below.

- *Routine Conditions:* These conditions are applicable to firefighters who are operating hoses or otherwise fighting fires from a distance, where no special clothing is necessary. According to Foster et al. [9], the limits proposed are 25 minutes at 100 °C and a thermal radiation limit of 0.024 cal/cm<sup>2</sup> sec (1kW/m<sup>2</sup>). According to Abbott et al. [10], routine conditions are those experienced in front of a small open fireplace, and present no real hazard to the firefighter. The firefighter can remain close to the fire safely without any protective clothing for a minute or two and extinguish it. Abbott associates conditional limits of 20-70 °C with thermal radiation of < 0.04 cal/cm<sup>2</sup> sec (1.67 kW/m<sup>2</sup>).
- *Hazardous Condition:* These conditions (described as "Ordinary" by Abbott et al.) are typical of those that would be encountered outside a burning room or small burning building. As reported by Hoschke [11], the lower bounds of this region are similar to firefighters ventilating a fire without water support, while the upper limits are applicable to those who are first into a burning building. Nonetheless, a "turnout" uniform is necessary to provide burn protection and to minimize thermal stress the firefighter may encounter. The range set by Foster et al. [9] has been taken to be at least 1 minute at 160 °C and a thermal radiation of 0.096 cal/cm<sup>2</sup> sec (4 kW/m<sup>2</sup>) and can be tolerated up to 10 minutes. Abbott et al. [10] describe this condition as lasting 10-20 minutes with air temperatures of 70 °C-300°C with thermal radiation of 0.04 cal/cm<sup>2</sup> sec to 0.30 cal/cm<sup>2</sup> sec (4.0 to 12.56 kW/m<sup>2</sup>). Recent work has shown that some simple wastebasket fires may output up to 40 kW/m<sup>2</sup>.
- *Critical Condition:* These conditions (described as "Emergency" by Abbott et al.) are not normally encountered by civilian firefighters. These conditions exist around a crashed aircraft when fiercely burning fuel exists. They may also be encountered during "flashover" of a large building fire. A proximity suit as well as special breathing apparatus must be employed when working with fires in this condition [11]. These conditions have been taken to be above the range of "Hazardous" conditions and ranging to beyond 235 °C and 0.23 cal/cm<sup>2</sup> sec (10 kW/m<sup>2</sup>) by Foster et al. [9]. Severe thermal problems and life threatening injuries are associated with these conditions. Abbott et al. [10] describe these conditions as having temperatures of 300 °C to 1200 °C and 0.30 cal/cm<sup>2</sup> sec to 5.0 cal/cm<sup>2</sup> sec (12.56 to 209.34 kW/m<sup>2</sup>).

## **Thermal Protective Clothing Needs**

Based on a multitude of occupational hazards associated with different job contents, a complex need for protection from thermally hazardous conditions exists. Development of these protective systems has been one of the major technical challenges for textile material scientists in the past. Several approaches have been implemented using different polymer fibers and finishes in a variety of combinations. The materials must be very thermally stable and yet be durable and flexible. Thermally protective garments that insulate well also impose a metabolic heat load burden on an individual involved in strenuous work. These and other conflicting requirements have often resulted in a multilayer approach though in many routine scenarios, single layer protective garments are widely used. Protective systems also often incorporate secondary materials such as harness, belts, reflective strips, fasteners and the like. The primary function of all these systems is the prevention or minimization of burn injury while allowing the wearer to perform the functions required by the job at hand. Measurement of heat transferred through such a broad array of heterogeneous media is complicated by effects related to conductive, convective and radiative transfer as well as mass transfer effects created by evaporation and condensation of volatiles in the garment layers.

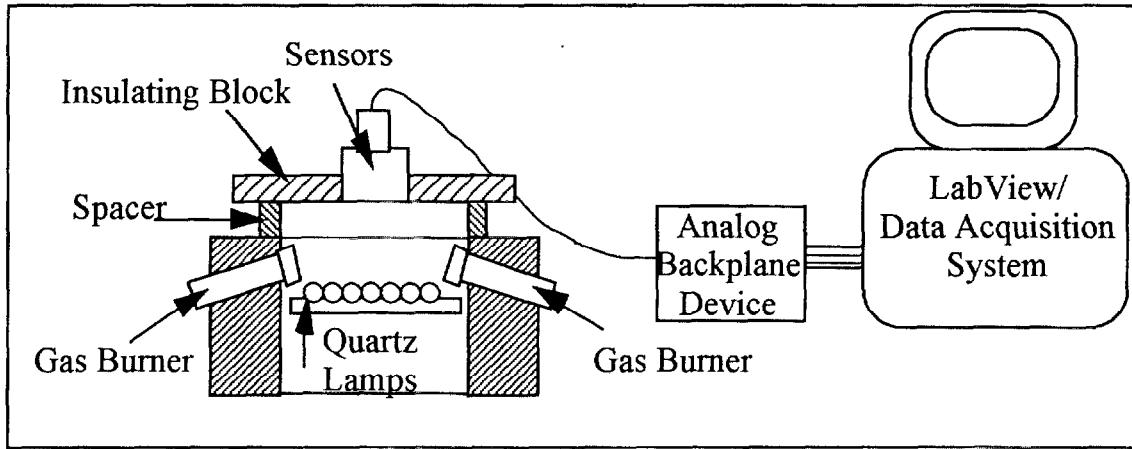
## **Experimental Approach**

Experiments were performed to compare the surface mounted thermocouple sensor, embedded thermocouple sensor, TPP sensor and a newly developed insulated copper sensor on the basis of:

- Flux read when exposed to a range of known thermal conditions.
- Response to thermal energies encountered while testing materials that react differently to intense thermal exposures.
- Predictions of skin burn injury.

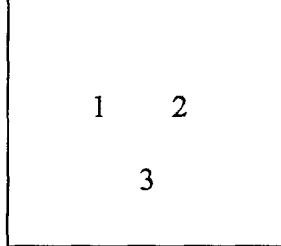
## **Bare Sensor Tests**

The experimental setup used to compare the insulated copper, surface mounted thermocouple, and embedded thermocouple sensors is shown in Figure 1.



**Figure 1:.** Sensor Test Set-Up.

Test sensors were mounted in a 5 x 5 inch (12.7 x 12.7 cm) insulating block and positioned at a fixed distance from the heat source. The sensor configuration for simultaneously testing is shown in Figure 2.



**Figure 2:.** Sensor Mounting Configuration.

The sensor output was fed to a 16-channel analog backplane device (National Instruments). The backplane device contained modules, which in addition to capturing nonlinear voltage readings from each sensor, isolated and linearized each signal. Output voltages were fed, from the analog backplane device, to an MIO board (AT-MIO-16F-5 DAQ) to generate time signatures for these signals. LabView software was used to translate voltage signals into temperature readings. Data was generated at a rate of 17-21 time/ temperature data set samples per second. The procedures used to calculate the heat flux for the insulated copper and surface thermocouple sensors are given in Appendix A. A proprietary computer program was used to calculate heat flux, in the case of the embedded thermocouple sensor.

The insulated copper, surface thermocouple and embedded thermocouple sensors were exposed simultaneously to the following conditions:

Condition 1: 100% radiant heat source @ 0.14 cal/cm<sup>2</sup>-sec nude exposure for 20 seconds  
heat source: bank of nine quartz tubes.

Condition 2: 100% radiant heat source @ 0.30 cal/cm<sup>2</sup>-sec nude exposure for 20 seconds  
heat source: bank of nine quartz tubes.

Condition 3: 50/ 50 convective/ radiant heat source @ 2.0 cal/cm<sup>2</sup>sec nude exposure for 5 seconds  
heat source: TPP test configuration - flames and quartz tubes

The TPP calorimeter was used to set the nominal heat flux for each exposure condition. Quadruplicate measurements were made at each exposure condition to determine the variability of consecutive thermal readings. For each trial, the insulating block was rotated clockwise  $\frac{1}{4}$  of a turn, to determine if the sensor response was position dependent. Also, three sensors of each type were tested to determine variability among individual sensors of the same type.

### Results

Tables 2 - 3 and Figures 3 - 5 show the results of comparative tests made at different thermal exposure conditions. Tables A3- A11 and Figures A1- A9 (Appendix A) provide complete results for the comparative tests.

Sensor performance was compared on the basis of:

- Flux readings, based on the TPP sensor as the referee.
- Variability in consecutive flux readings, indicated by the range and standard deviation of measurements.
- Sensor response time, recorded in the first second of the heat exposure.
- Variability among individual sensors of the same type.

**Table 2. Comparison of Heat Flux Read by Different Sensors<sup>1</sup>**

Sensor	Average Heat Flux <sup>2</sup> (cal/cm <sup>2</sup> .sec)	% Diff. <sup>3</sup>	Range <sup>4</sup> (cal/cm <sup>2</sup> .sec)	Response Time <sup>5</sup> (cal/cm <sup>2</sup> .sec <sup>2</sup> )
Thermal Exposure: 0.14 cal/cm <sup>2</sup> .sec				
insulated copper	0.14 $\pm$ 0.01	-	0.11 - 0.17	0.28 $\pm$ 0.00
embedded thermocouple	0.14 $\pm$ 0.01	-	0.12 - 0.18	0.30 $\pm$ 0.00
surface thermocouple	0.13 $\pm$ 0.01	7.14	0.06 - 0.14	0.35 $\pm$ 0.04
Thermal Exposure: 0.30 cal/cm <sup>2</sup> .sec				
insulated copper	0.29 $\pm$ 0.01	3.33	0.26 - 0.32	1.24 $\pm$ 0.02
embedded thermocouple	0.29 $\pm$ 0.04	3.33	0.24 - 0.40	0.77 $\pm$ 0.02
surface thermocouple	0.27 $\pm$ 0.02	10.00	0.13 - 0.31	0.68 $\pm$ 0.09
Thermal Exposure: 2.00 cal/cm <sup>2</sup> .sec				
insulated copper	1.97 $\pm$ 0.16	1.50	1.67 - 2.53	9.69 $\pm$ 0.20
embedded thermocouple	1.88 $\pm$ 0.19	6.00	1.48 - 2.41	8.22 $\pm$ 0.86
surface thermocouple	1.30 $\pm$ 0.27	35.00	0.45 - 1.62	2.23 $\pm$ 0.11

<sup>1</sup>Reported values are the means of quadruplicate readings.

<sup>2</sup>Average flux calculated as the mean of the heat flux throughout the test exposure for sensors 1-3 from time t=0 sec. These data are shown in Appendix A.

<sup>3</sup>Percent difference of heat flux values compared to the TPP sensor reading.

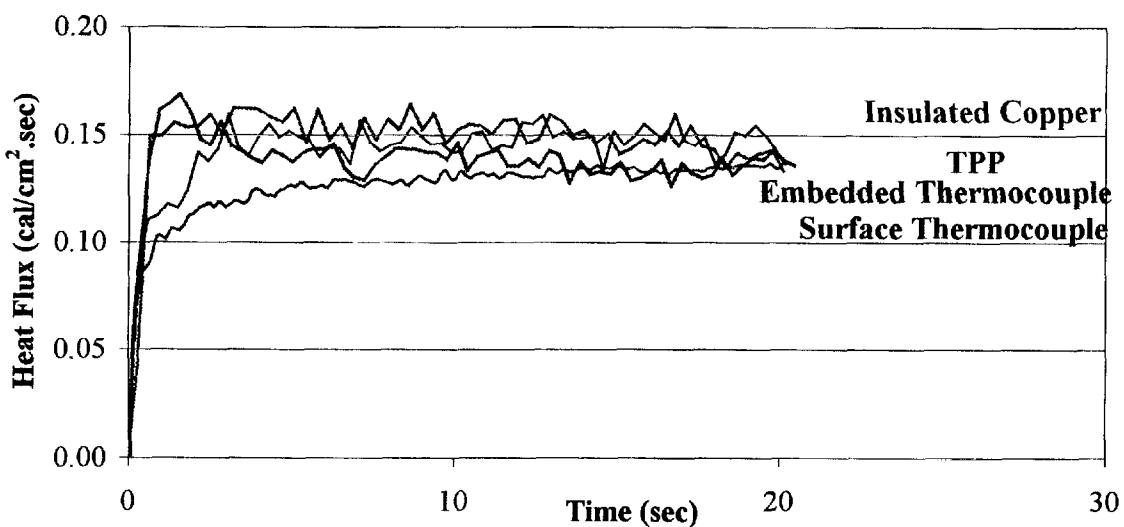
<sup>4</sup>Range observed in quadruplicate readings of three sensors.

<sup>5</sup>Response time measured in the first second of the heat exposure.

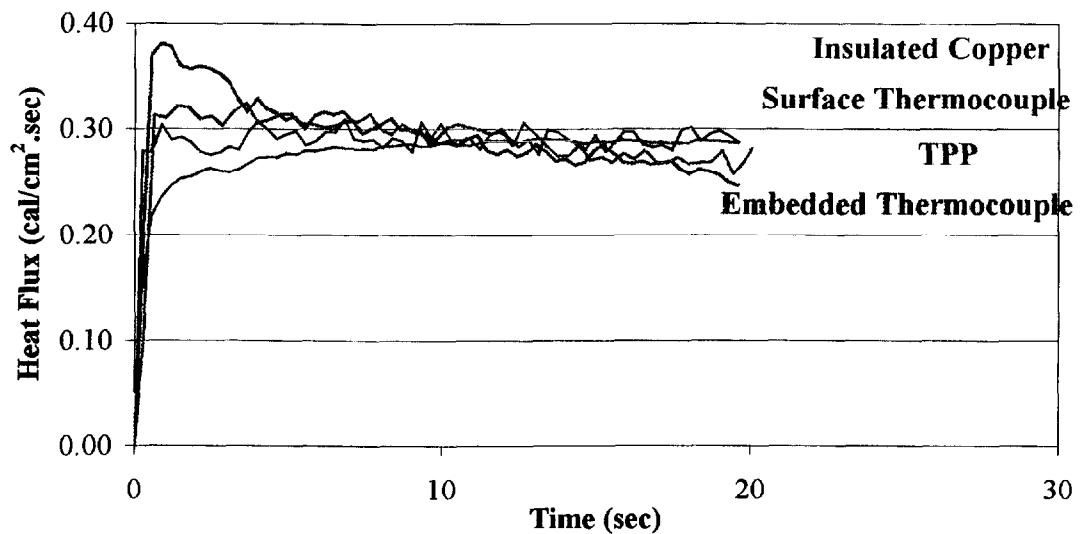
**Table 3. Variability of Sensor Heat Flux Reading<sup>1</sup>**

Sensor #	Average Heat Flux (cal/cm <sup>2</sup> .sec) insulated copper	Average Heat Flux (cal/cm <sup>2</sup> .sec) embedded thermocouple	Average Heat Flux (cal/cm <sup>2</sup> .sec) surface thermocouple
Thermal Exposure: 0.14 cal/cm <sup>2</sup> .sec			
# 1	0.15 ± 0.01	0.14 ± 0.01	0.13 ± 0.01
# 2	0.14 ± 0.01	0.14 ± 0.01	0.13 ± 0.01
# 3	0.14 ± 0.01	0.14 ± 0.01	0.13 ± 0.01
Thermal Exposure: 0.30 cal/cm <sup>2</sup> .sec			
# 1	0.30 ± 0.01	0.29 ± 0.03	0.30 ± 0.02
# 2	0.28 ± 0.01	0.31 ± 0.04	0.26 ± 0.02
# 3	0.29 ± 0.01	0.30 ± 0.04	0.28 ± 0.01
Thermal Exposure: 2.00 cal/cm <sup>2</sup> .sec			
# 1	2.10 ± 0.14	1.74 ± 0.12	1.33 ± 0.29
# 2	1.99 ± 0.16	1.96 ± 0.24	1.22 ± 0.26
# 3	1.96 ± 0.18	1.93 ± 0.21	1.33 ± 0.26

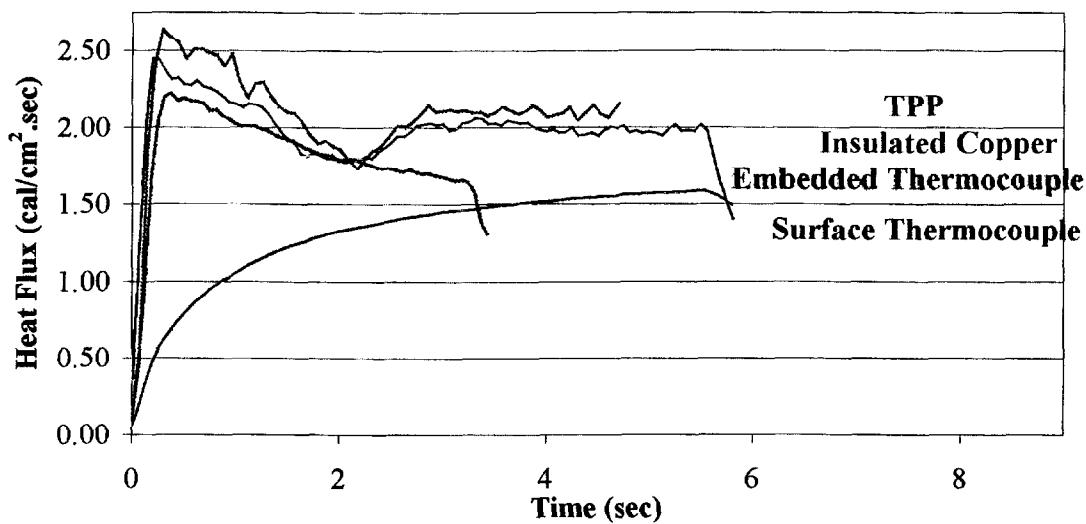
<sup>1</sup>Reported values are calculated as the mean of quadruplicate readings.



**Figure 3: Mean Flux for Sensors 1-3 Averaged over 4 Trials @ 0.14 cal/cm<sup>2</sup>.sec Nude Exposure.**



**Figure 4:.** Mean Flux for Sensors 1-3 Averaged over 4 Trials @  $0.30 \text{ cal/cm}^2 \cdot \text{sec}$  Nude Exposure.



**Figure 5:.** Mean Flux for Sensors 1-3 Averaged over 4 Trials @  $2.00 \text{ cal/cm}^2 \cdot \text{sec}$  Nude Exposure.

Our observations regarding these comparative data can be summarized as follows:

- Insulated copper sensor reading of heat flux corresponds closely with the TPP sensor measurements at the 0.14 cal/cm<sup>2</sup>sec and 0.30 cal/cm<sup>2</sup>sec heat exposures, as well as the 2.00 cal/cm<sup>2</sup>sec exposure. However, because of the fact that there cannot be a perfect insulator around the insulated copper disk, losses from the disk have to be accounted for. This is done by using a calibration factor to bring the insulated copper sensors into agreement at the highest heat exposure levels. A calibration equation was found, based on experimental results used in the design of the transducer, to correct for heat losses in the sensor. This can be seen in Appendix A.
- The embedded thermocouple sensor provides a reasonably accurate estimate of average heat flux for all levels of thermal exposure. However, heat loss is seen at 0.30 cal/cm<sup>2</sup>sec and 2.00 cal/cm<sup>2</sup>sec heat exposures. These discrepancies are typically adjusted for, using calibration factors.
- The embedded thermocouple sensor produces more variability in heat flux readings (between individual sensors). This can be attributed to differences in the thermocouple bead position among different sensors. This trait requires independent calibration of each individual sensor.
- The insulated copper sensor provides a response that is most like that of the TPP sensor. This is to be expected, since they are both slug-type calorimeter sensors. It is believed that the average response of the embedded thermocouple sensor to the 2.00 cal/cm<sup>2</sup>sec exposure condition is somewhat lower than insulated copper because of heat loss.
- Both the insulated copper and embedded thermocouple sensors provide consistent average reading of heat flux in repeated measurements for the exposure conditions tested. The insulated copper sensor, however, is more repeatable than the embedded thermocouple and surface thermocouple sensors at all thermal exposure levels.
- The surface thermocouple type sensor consistently estimates accurate heat flux, compared to the TPP sensor for the 0.14 cal/cm<sup>2</sup>sec and 0.3 cal/cm<sup>2</sup>sec heat exposures. However, at the 2.0 cal/cm<sup>2</sup>sec exposure, the surface thermocouple sensor gives a considerably lower response. This might be due to the fact that the thermocouple bead is on the surface of an insulating material, which would reflect some of the radiative energy away from the surface of the sensor.

#### TPP Type Tests

A second series of experiments were performed to compare the insulated copper, surface thermocouple and embedded thermocouple sensor readings when testing materials in a "TPP test" type set-up. These experiments were performed to understand how, in testing actual thermal protective materials in manikin tests, each sensor would respond when encountering different responses from materials, such as offgassing or rapid heat transmission. The test

materials chosen for this demonstration include Flame Retardant Cotton, Nomex® III, and Wool (Table 4).

**Table 4. Test Fabrics**

Fabric	Weight (oz/yd <sup>2</sup> )	Thickness (mm) <sup>1</sup>	Flame Resistance
Nomex® III	5.33	0.53	Inherent
FR Cotton	6.93	0.43	Treated
Wool	10.23	0.65	Inherent

<sup>1</sup> Thickness measured under pressure of 0.5 gf/cm<sup>2</sup> using an Electronic Thickness Tester.

The experimental arrangement was equivalent to a TPP test with a ¼ inch space configuration: materials were tested as shown in Figure 2. Three sensors were mounted in a 5 x 5 inch (12.7 x 12.7 cm) insulating block and positioned at a fixed distance from the laboratory heat source as shown in Figure 2. Position 1 held the insulated copper sensor, Position 2 the embedded thermocouple sensor, and Position 3 the surface thermocouple sensor. Data acquisition was the same as in the previous tests.

The TPP calorimeter was used to establish heat flux for each exposure condition. The test exposure was a 50/50 convective/radiant source at 2.00 cal/cm<sup>2</sup> sec for 10 seconds. Quadruplicate measurements were made at each exposure condition to determine the variability of consecutive thermal readings. For each trial, the insulating block was rotated clockwise ¼ of a turn, to determine if the sensor response was position dependent. The experimental procedure was repeated for each material. Because the TPP calorimeter could not be tested simultaneously with the other sensors, it was tested by itself using the same experimental setup.

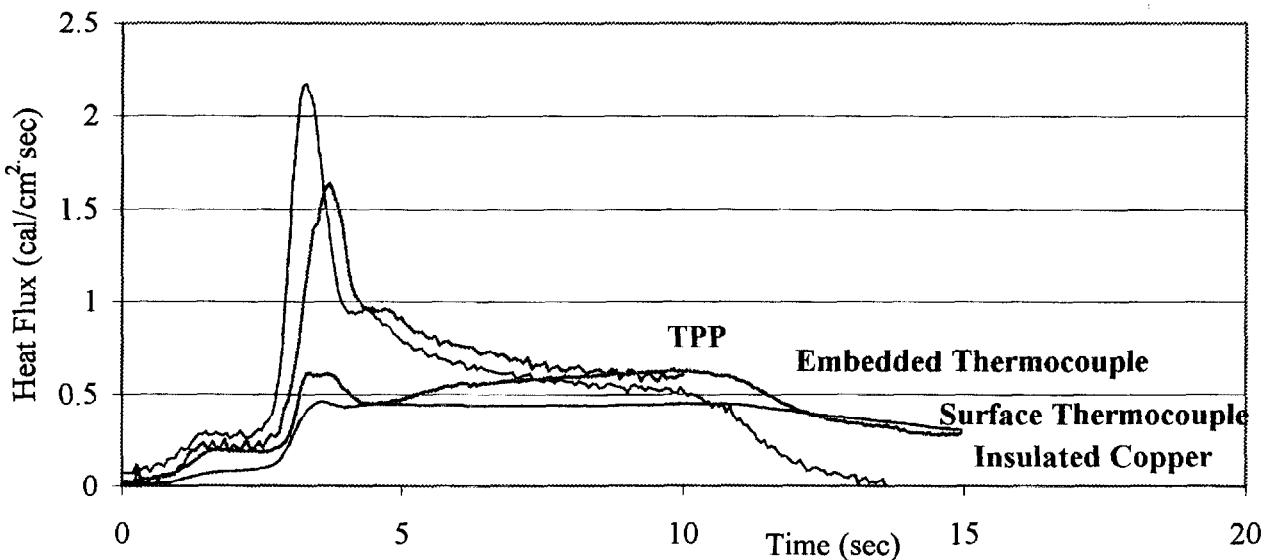
### Results

Figures 6 - 8 show the average results of the response of the different thermal sensors when testing different materials in a “TPP test” type set-up. Tables A12 – A13 (Appendix A) provide complete results for the comparative tests.

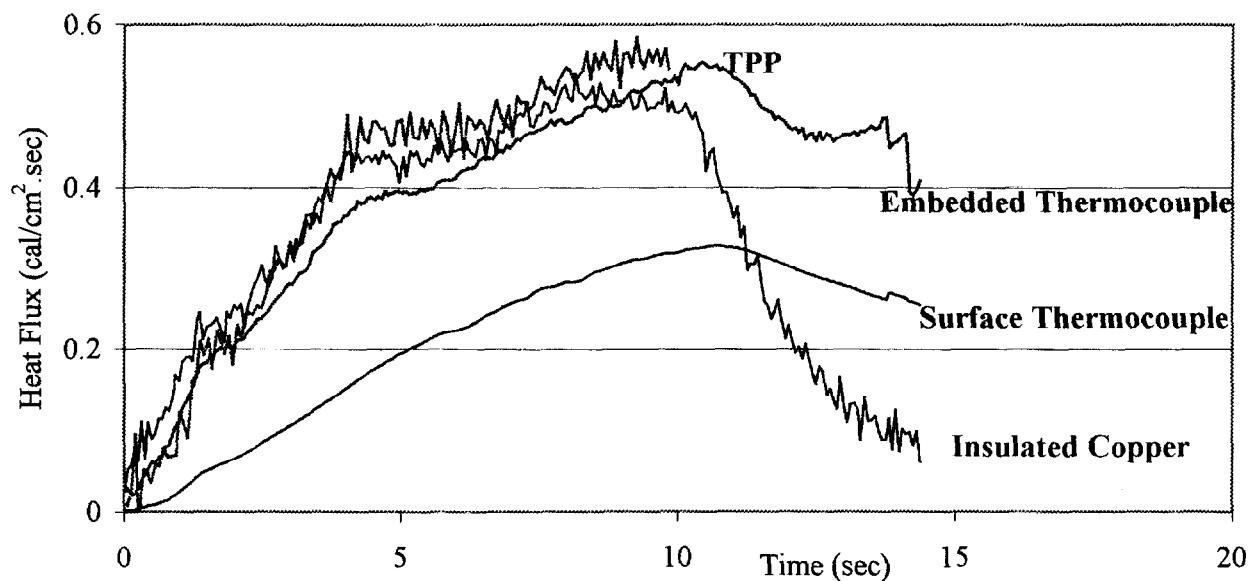
Sensor performance was evaluated on the following considerations:

- The accuracy of each individual sensor reading compared with the heat flux read by the referee TPP calorimeter sensor.

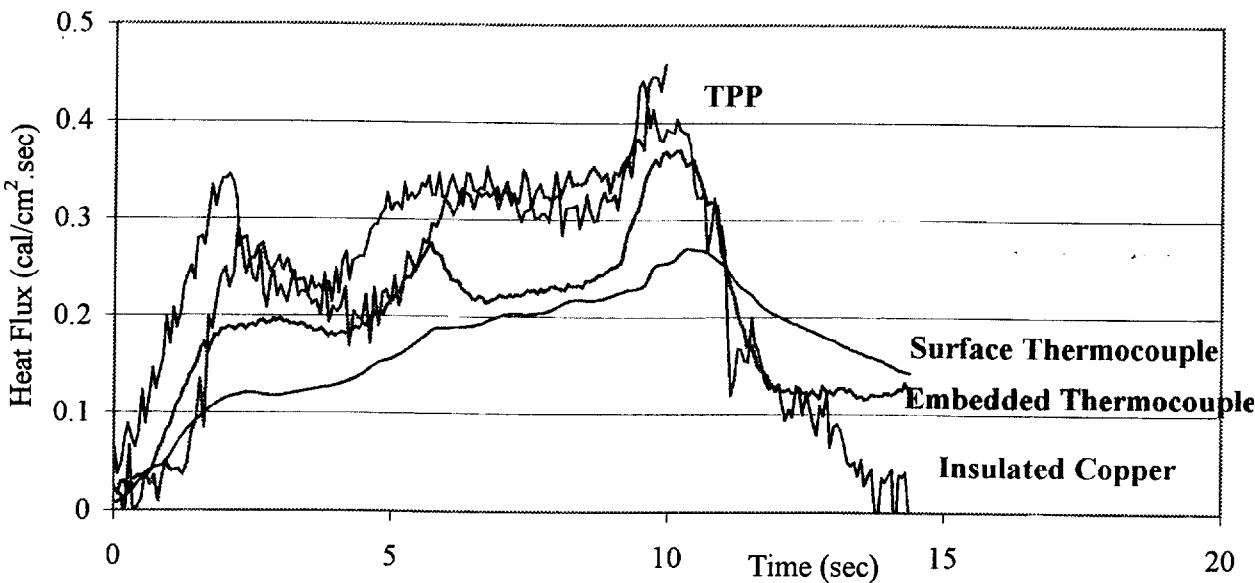
- The accuracy of each individual sensor burn prediction and computed TPP index compared with the predicted burn and TPP index by the referee TPP calorimeter sensor.



**Figure 6: Average of Four Trials @ 2.0 cal/cm<sup>2</sup>/sec for 10 sec. With FR Cotton.**



**Figure 7: Average of Four Trials @ 2.0 cal/cm<sup>2</sup>/sec for 10 sec. With Nomex® III.**



**Figure 8: Average of Four Trials @ 2.0 cal/cm<sup>2</sup>.sec for 10 sec. With Wool.**

Our observations regarding these comparative data can be summarized as follows:

- A very complex behavior is exhibited by the FR cotton sample as can be seen in Figure 6. The process of heat transfer through the cotton fabric can be divided into three distinct stages. The first stage is an initial heating period that lasts for approximately 2.5 to 3.0 seconds after the onset of the heat exposure. This phase is followed by a second stage occurring between 3.0 to 5.0 seconds after the test is initiated, in which heat is generated and transferred rapidly through the fabric. This generation of heat is the result of the exhaustion of FR chemicals and the ignition of the fabric, which is evident in the liquid condensate that is present on the surface of the sensors. This is also very evident by the responses of the TPP and insulated copper sensors. The final stage is a more moderate heat transfer (> 5.0 seconds). This observed reduction of heat transmission can be attributed to the formation of an insulative char. This is a result of the carbonization of the cellulosic material.
- The response of the sensors to the second stage of the FR cotton sample, can be separated into two distinct groups. It is evident that the slug calorimeter type sensors respond to this rapid transmission of heat and offgassing. However, the embedded thermocouple and surface thermocouple sensors give a response that is slower and lower than that of the insulated copper and TPP sensors. This is partly due to the fact that these sensors utilize thermocouples that are either on the surface or buried in a block of insulating material, slowing response and reflecting energy away from the surface of the sensor. The copper based sensors also provide a larger integrating measurement surface area for sensing mass heat transfer.

- The rate of heat transfer for the Nomex<sup>®</sup> III sample was relatively fast for the first 3.5 to 4.0 seconds of exposure, as indicated by the slopes of the graphs in Figure 7. However, after 4.0 seconds, backside flaming was observed, and lasted typically until the end of the test. This can be pointed out by the change in slope. This was probably due to the small contribution that the heat released by ignition contributed to the overall heat transfer. Again, it was seen that the surface thermocouple sensor did not respond to this change in heat transfer.
- Three distinct peaks can be seen in Figure 8 for the Wool samples tested. These peaks are results of fabric swelling and shrinkage throughout the exposure thus changing the thermal thickness of the fabric and air gap. This is evident by the resulting char present on each sensor as well as the swelling and break open that occurs in the center of the fabric.

### Burn Predictions

The next step taken was to compare the burn predictions developed from readings from the embedded thermocouple, insulated copper, and surface thermocouple sensors. A proprietary algorithm was used to compute burn injury information in the case of the embedded thermocouple sensor. For the insulated copper, and surface thermocouple burn prediction, a model was developed from first principles and is described in Appendix B. Table 5 shows a comparison of burn prediction made in the experiments that exposed bare sensors to a heat source. Table 6 shows the burn predictions made in the “TPP” type experiments on the test materials.

**Table 5. Comparisons of Burn Predictions for Nude Exposures**

Sensor	Time to 2 <sup>nd</sup> Degree Burn (sec)	Time to 3 <sup>rd</sup> Degree Burn (sec)
Thermal Exposure: 0.14 cal/cm <sup>2</sup> sec		
TPP <sup>1</sup>	20.24 ± 0.80	---
TPP <sup>2</sup>	19.71 ± 0.77	---
insulated copper	20.73 ± 0.56	---
embedded	23.59 ± 2.31	---
thermocouple		
surface	24.59 ± 0.44	---
thermocouple		
Thermal Exposure: 0.30 cal/cm <sup>2</sup> sec		
TPP <sup>1</sup>	7.47 ± 0.54	N/A
TPP <sup>2</sup>	6.97 ± 0.07	18.00 ± 0.05
insulated copper	7.45 ± 0.33	18.48 ± 0.48
embedded	6.24 ± 0.36	17.50 ± 0.48
thermocouple		
surface	8.51 ± 0.75	18.74 ± 0.75
thermocouple		
Thermal Exposure: 2.00 cal/cm <sup>2</sup> sec		
TPP <sup>1</sup>	0.84 ± 0.01	N/A
TPP <sup>2</sup>	0.77 ± 0.07	4.94 ± 0.10
insulated copper	0.57 ± 0.01	4.91 ± 0.10
embedded	0.69 ± 0.07	---
thermocouple		
surface	1.58 ± 0.07	---
thermocouple		

<sup>1</sup>Estimated time to burn based on Stoll data from TPP standard test method.

<sup>2</sup>Calculated burn times based on burn model used for other three sensors.

**Table 6. Comparison of Burn Results for 2.00 cal/cm<sup>2</sup>sec TPP Application.**

Sensor	Time to 2 <sup>nd</sup> Degree Burn <sup>1</sup> (sec)	TPP Value <sup>2</sup> (cal/cm <sup>2</sup> )	TPP/Weight <sup>3</sup>
FR Cotton (6.93 oz/yd <sup>2</sup> )			
TPP	3.76	7.52	1.06
insulated copper	3.31	6.62	0.96
embedded	5.72	11.44	1.65
thermocouple			
surface	6.84	13.68	1.97
thermocouple			
Nomex® III (5.33 oz/yd <sup>2</sup> )			
TPP	6.07	12.14	2.28
insulated copper	6.09	12.18	2.29
embedded	6.81	13.62	2.56
thermocouple			
surface	11.31	22.62	4.24
thermocouple			
Wool (10.23 oz/yd <sup>2</sup> )			
TPP	9.09	18.18	1.78
insulated copper	7.99	15.98	1.56
embedded	10.76	21.52	2.10
thermocouple			
surface	14.79	29.58	2.89
thermocouple			

<sup>1</sup>Burn time as calculated by burn program.

<sup>2</sup>TPP Value = (Time to 2<sup>nd</sup> Degree Burn) x (Heat Flux)

<sup>3</sup>Value obtained by dividing the TPP value by the weight of the fabric.

Some observations on these data can be summarized as follows:

- In the bare sensor tests (Table 5), predicted burn times computed from TPP sensor response using the Stoll data from TPP standard test method and using our burn model, agree closely.
- In the bare sensor tests (Table 5), predicted burn times for all sensors are comparable with the TPP sensor times, with the embedded thermocouple and surface thermocouple sensors yielding somewhat longer times to burn at 0.14 cal/cm<sup>2</sup>sec.
- The insulated copper sensor produces the more consistent result, as indicated by its low standard deviation of repeated measurements. This is essential when comparing results from multiple sensors. The variability among sensors is greatest for the embedded thermocouple sensors at the low exposure level, as seen in the standard deviation.

- The insulated copper sensor's predicted burn times for 0.14 and 0.30 cal/cm<sup>2</sup> sec exposures, correspond more closely to the burn times indicated by the TPP calorimeter, than do the surface thermocouple and the embedded thermocouple sensors (Table 6). This can be explained by the fact that both are copper slug calorimeters. However, the response of the insulated copper sensor is slightly faster than that of the TPP sensor, due to the fact that its slug is about ten times as small as the TPP sensor. This is evident in its shorter predicted time to burn relative to the TPP sensor at the 2.00 cal/cm<sup>2</sup> sec exposure.
- The surface thermocouple sensors regularly overpredict time to nude second degree burn compared to the TPP, insulated copper and embedded thermocouple sensors.
- Insulated copper and the TPP sensor results agree closely on TPP value for FR Cotton and Nomex® III. Agreement between insulated copper and the TPP sensor results for Wool is somewhat less close due to the complex and rapid changes in physical properties that occur.
- The embedded thermocouple sensor overpredicts protection for FR Cotton and Wool but agrees reasonably well with the TPP sensor and the insulated copper for Nomex® III.
- The surface thermocouple sensors substantially overpredict protection in all cases. For FR Cotton and Nomex® III, overprediction is by more than 80%.
- The surface thermocouple sensor responds very differently than the other sensors in the TPP laboratory tests. This might be due to the fact that the thermocouple bead is on the surface of an insulating material, which would reflect energy away from the surface of the sensor, leading to a much smaller local heat flux reading. Because of the response to heat flux seen in the surface thermocouple sensor, it is evident that its burn prediction and TPP index will be higher than the other sensors.

### Conclusions

The NCSU insulated copper sensor is emerging as a reliable and versatile thermal sensor for applications related to evaluating the thermal protective performance of firefighter's protective clothing. Laboratory tests indicate that the insulated copper sensor provides a consistent and stable reading over the wide range thermal exposures of interest in this application. They show that the insulated copper sensor registers heat flux much like the TPP calorimeter, a device with a long history of use in bench scale testing of thermally protective materials. At the same time, the insulated copper sensor is packaged in a smaller and far less bulky housing than is required to insulate the TPP calorimeter against heat loss. The insulated copper sensor has the additional advantage of possessing a small mass in comparison to the TPP calorimeter (1.3 grams vs. 17.9 grams). This is an important consideration, since the smaller mass of the insulated copper sensor should significantly reduce heat sink effects associated with the use of the TPP calorimeter. This should contribute to improve the accuracy of the bench top TPP tests when used in sample mounting configurations that require intimate contact between the thermal sensor and the test fabric.

Although the sensors that utilize relatively insulative materials with surface mounted thermocouples and embedded thermocouples, perform comparatively well in nude thermal tests, they lack the durability in use that can be expected from the insulated copper device. Most significantly, the insulated copper sensor overcomes a significant drawback associated with this type of sensor: it does not require an inverse heat transfer calculation to estimate heat flux. This avoids errors associated with thermocouple location, and the mathematics of the heat transfer calculations. Direct heat flux measurements, using the insulated copper sensor, circumvent these errors and provide a more accurate direct reading.

We are initiating experiments to confirm the efficiency of using the insulated copper and embedded thermocouple sensors in the following applications:

- Instrumented manikin tests of full garments: Experiments to compare the performance of the insulated copper and embedded thermocouple sensors in simulated flash fire (2.00 cal/cm<sup>2</sup>/sec) exposures when installed in the NCSU PyroMan manikin. These tests will show a better comparison of 2<sup>nd</sup> and 3<sup>rd</sup> degree burns as well.
- Long term exposures, to test the viability of sensors at high heat fluxes over long exposure times. This data will provide a determination of how long each sensor will last before it fails. Tests will be made and compared to calculated predictions based on the degradation temperatures of each sensors' polymeric components.

### Future Directions

Both the calorimeter type and thermocouple type sensors, which have been investigated in this study, are limited to relatively short exposure duration, usually a few seconds at a time. These sensors are constructed of materials that retain heat during the exposure sequence. Subsequently, the sensor internal temperature rises to levels that would make the sensor unable to accurately measure the incident heat flux. To a certain extent, all of these sensors become impaired at long exposure durations.

Other sensor technologies have also been found to have major limitations for our application. In-depth thermopile calorimeters are very flux range specific and commercial circular foil type calorimeters are limited to fluxes above 3.5 w/sq cm. Both of these types are limited to surface temperatures of about 400 F unless metals are used throughout. However, epoxies are often unavoidably used in the construction of many of these sensors. The in-depth thermopile and the circular foil calorimeters can be precision calibrated to specific temperature ranges, however, at high exposures sensitivity drops off rapidly [17].

A review of the literature showed that there are, at least, two water-cooled thermal sensors available for use. Thermogage<sup>TM</sup> is a water-cooled transducer that measures the absorbed heat flux based on the reading of a pair of differential thermocouples [15] placed at the center and the circumference of thin circular Constantan foil. Besides the information attached in an

Appendix C, very little technical information is available about this transducer.

A second water-cooled sensor, made by Hy-Cal Engineering [16], is based on the same principle of absorbed heat flux measurement. Both sensors have a built-in cooling system that removes the heat absorbed during exposure. This heat removal process prevents the sensors' temperature from rising and allows these sensors to maintain their temperature gradients with the heat source and function much longer than the non-cooled sensors. However, because of the thermal inertia of their cooling systems and their relatively slow response time, these sensors are not suitable for measurement of rapid transient heat transfers [17]. The capability and accuracy of these sensors is limited only to those exposure types, levels and durations that are indicated by the sensor's manufacturers. Elaborate and expensive periodical calibration routines are also required to guaranty proper performance of these two sensors. Furthermore, the accuracy of any cooled sensor is directly related to the characteristics of the cooling system associated with the sensor. In order to accurately assess the incident heat flux over long exposure durations by cooled sensors, an precise evaluation of the heat evacuated by the sensor's cooling system is required. Other variables and thermal characteristics of the cooled sensor, which is modeled as a heat exchanger, are also needed for an accurate heat flux evaluation.

None of the reviewed sensors would accommodate the source type, fluctuations, intensity and duration of the incident heat flux endured by a firefighter. This state represents a highly variable and unsteady set of complex thermal conditions. To assess these conditions, a sensor should have the following attributes:

- The capability to sense conductive, convective and radiative sources,
- The capability to perceive a wide range of exposure levels,
- The capability to assess transient and unsteady heat fluxes, and
- The capability to withstand long exposure durations

It would also be desirable that the heat that accumulates within a firefighter clothing system during a prolonged exposure could be sensed in real time to help warn of impending skin burns ahead of time.

To accommodate these special requirements, an "intelligent" heat sensing set-up should be developed. A calorimeter-type sensor, with a high sensitivity and short response time, such as the insulated copper sensor would be at the core of this sensing system. This would allow the system to accurately sense and measure a wide range of incident heat fluxes. Part of the assemblage would be an adequate cooling system with known characteristics and parameters. This cooling system would prevent heating of the sensor and maintain its sensing capabilities and sensitivity over durations relevant to field exposure scenarios. The intelligence of the assemblage would rely on associated software and hardware to continuously assess and tally the accumulated heat within the firefighter clothing system and ultimately to raise an alarm and warn the wearer. By this mean, harmful exposures and skin burns could be prevented ahead of time.

Due to its proven sensitivity, ruggedness and light weight, the insulated copper calorimeter developed at T-PACC is currently a prime candidate for upgrade to a cooled, field installable sensor system. Possible enhancements to be explored are solid state, fluidless cooling systems, data telemetry to a remote computer and mounting hardware conformable to field gear.

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## **Appendix A**

### **Procedures and Data for Calculating Heat Flux**

### Sensor Calculations

For the insulated copper sensor, incident heat flux was calculated using the following equation:

$$q = \frac{M C_p C_l}{A} \frac{dT}{dt} + K_l(T_d - T_i)$$

where:

$q$  = Incident heat flux ( $\text{cal/cm}^2\text{-sec}$ )

$M$  = Mass of calorimeter slug (grams)

$C_p$  = Heat capacity of copper ( $\text{cal/g } ^\circ\text{C}$ )

$C_l$  = Thickness factor as experimentally determined

$A$  = Disk area ( $\text{cm}^2$ )

$K_l$  = Heat loss coefficient as experimentally determined ( $\text{cal/cm}^2\text{-sec } ^\circ\text{C}$ )

$T_d$  = Surface temperature of disk at time  $t$

$T_i$  = Initial or ambient temperature

The physical constants used for the computation of incident heat flux for each sensor are shown below.

**Table A1. Copper Slug Sensor Specifications**

Sensor	Mass (g)	Area ( $\text{cm}^2$ )	$\epsilon$	$C_l$	$K_l$ ( $\text{cal/cm}^2\text{-sec } ^\circ\text{C}$ )	$C_p$ ( $\text{cal/g } ^\circ\text{C}$ )
TPP	17.89	12.56	0.95	--	--	0.0927
Insulated copper	1.31	0.99	0.95	1.04	0.00358	0.0927

For the surface thermocouple sensor, heat transfer is treated as transient heat conduction into a semi-infinite slab. Based on surface temperature,  $T_s$ , the incident heat flux,  $q$ , can be estimated using the following equation:

$$q = \frac{\sqrt{\pi k\rho C_p}}{2\sqrt{t}} (T_s - T_\infty)$$

Where

$k$  = thermal conductivity

$\rho$  = density

$T_s$  = surface temperature at time  $t$

$T_\infty$  = the initial or ambient temperature

This equation was used, in conjunction with the following physical constants, to represent a skin simulation:

**Table A2. Skin and Skin Simulant Specifications**

Properties	Epidermis	Dermis	Skin Simulant
$k$ (W/m·K)	0.225	0.523	0.97
$\rho$ (kg/ m <sup>3</sup> )	1200	1200	1877
$C_p$ (J/kg·K)	3598	3222	1205
$k\rho c$ (J <sup>2</sup> /m <sup>4</sup> ·degC <sup>2</sup> ·s)	$1.1 \times 10^6$	$2.0 \times 10^6$	$2.2 \times 10^6$

Additional details, concerning calculations that involve the surface thermocouple sensor can be found in reference 4.

In the case of the embedded thermocouple sensor, a proprietary computer program was used to calculate heat flux.

The following tables give the results of applying these calculation procedures for each sensor at 0.14, 0.30, and 2.0 cal/cm<sup>2</sup>·sec:

**Table A3: Sensors 1-3 Averages of Mean Heat Flux @ 0.14 cal/cm<sup>2</sup>.sec Nude Exposure.**

Embedded Thermocouple		Surface Thermocouple		Insulated Copper	
Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)
0.00	0.01	0.00	0.00	0.00	0.00
0.29	0.09	0.23	0.07	0.23	0.07
0.61	0.14	0.54	0.09	0.54	0.11
0.93	0.16	0.85	0.10	0.85	0.11
1.24	0.16	1.16	0.10	1.16	0.12
1.56	0.17	1.48	0.11	1.47	0.12
1.87	0.16	1.79	0.11	1.79	0.12
2.19	0.15	2.10	0.11	2.10	0.14
2.50	0.14	2.41	0.12	2.41	0.14
2.82	0.16	2.72	0.12	2.72	0.14
3.14	0.14	3.04	0.12	3.03	0.16
3.45	0.14	3.35	0.12	3.34	0.14
3.77	0.14	3.66	0.12	3.66	0.14
4.08	0.14	3.97	0.12	3.97	0.15
4.40	0.14	4.28	0.12	4.28	0.15
4.71	0.14	4.59	0.12	4.59	0.15
5.03	0.14	4.90	0.13	4.90	0.15
5.34	0.14	5.22	0.13	5.22	0.15
5.66	0.14	5.53	0.13	5.53	0.15
5.98	0.14	5.84	0.13	5.84	0.14
6.29	0.15	6.15	0.13	6.15	0.14
6.61	0.14	6.46	0.13	6.46	0.14
6.92	0.13	6.77	0.13	6.77	0.14
7.24	0.13	7.08	0.13	7.09	0.16
7.56	0.14	7.40	0.13	7.40	0.15
7.87	0.14	7.71	0.13	7.71	0.14
8.19	0.14	8.02	0.13	8.02	0.14
8.50	0.14	8.33	0.13	8.33	0.15
8.82	0.14	8.64	0.13	8.65	0.15
9.14	0.14	8.96	0.13	8.96	0.15
9.45	0.14	9.27	0.13	9.27	0.15
9.77	0.14	9.58	0.13	9.58	0.15
10.08	0.15	9.89	0.13	9.89	0.14
10.40	0.13	10.20	0.13	10.20	0.14
10.71	0.14	10.52	0.13	10.52	0.15
11.02	0.14	10.83	0.13	10.83	0.15
11.34	0.14	11.14	0.13	11.14	0.14
11.66	0.14	11.45	0.13	11.45	0.14

11.97	0.14	11.76	0.13	11.76	0.14
12.29	0.14	12.07	0.13	12.08	0.16
12.60	0.13	12.39	0.13	12.39	0.15
12.92	0.14	12.70	0.13	12.70	0.16
13.23	0.14	13.01	0.13	13.01	0.15
13.55	0.13	13.32	0.13	13.32	0.15
13.86	0.14	13.64	0.13	13.63	0.15
14.18	0.13	13.95	0.13	13.94	0.15
14.49	0.13	14.26	0.13	14.26	0.15
14.80	0.13	14.57	0.13	14.57	0.13
15.11	0.14	14.88	0.13	14.88	0.15
15.42	0.13	15.19	0.13	15.19	0.14
15.74	0.13	15.51	0.13	15.50	0.15
16.05	0.13	15.82	0.13	15.81	0.15
16.36	0.14	16.13	0.13	16.12	0.15
16.67	0.13	16.44	0.13	16.43	0.15
16.99	0.14	16.75	0.13	16.74	0.16
17.30	0.13	17.06	0.13	17.05	0.15
17.61	0.13	17.38	0.13	17.36	0.14
17.92	0.13	17.69	0.13	17.67	0.15
18.23	0.14	18.00	0.13	17.98	0.14
18.54	0.13	18.31	0.13	18.30	0.14
18.86	0.14	18.62	0.14	18.61	0.15
19.17	0.14	18.93	0.14	18.92	0.15
19.49	0.14	19.24	0.14	19.23	0.15
19.81	0.14	19.56	0.14	19.54	0.15
20.13	0.14	19.87	0.13	19.85	0.14
20.44	0.14	20.18	0.14	20.16	0.14
<b>Average</b>	0.14	<b>Average</b>	0.13	<b>Average</b>	0.14

**Table A4: TPP Heat Flux @ 0.14 cal/cm<sup>2</sup>.sec Nude Exposure.**

TPP Trial 1		TPP Trial 2		TPP Trial 3		TPP Trial 4		TPP Average	
Time (sec.)	Flux (cal/cm <sup>2</sup> . s)								
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.27	0.05	0.28	0.04	0.26	0.04	0.27	0.04	0.27	0.04
0.63	0.15	0.64	0.15	0.63	0.15	0.63	0.15	0.63	0.15
1.00	0.13	1.02	0.15	1.01	0.17	1.00	0.15	1.00	0.15
1.38	0.16	1.39	0.16	1.38	0.16	1.37	0.15	1.38	0.16
1.77	0.16	1.76	0.15	1.76	0.16	1.75	0.14	1.76	0.15
2.14	0.15	2.12	0.15	2.14	0.17	2.12	0.15	2.13	0.15

2.50	0.16	2.48	0.17	2.50	0.16	2.49	0.15	2.49	0.16
2.86	0.16	2.84	0.15	2.87	0.14	2.85	0.15	2.85	0.15
3.21	0.17	3.21	0.15	3.24	0.17	3.21	0.16	3.22	0.16
3.57	0.16	3.59	0.17	3.65	0.16	3.58	0.16	3.60	0.16
3.93	0.16	3.99	0.17	4.02	0.15	3.95	0.16	3.97	0.16
4.28	0.14	4.35	0.15	4.38	0.18	4.47	0.16	4.37	0.16
4.64	0.15	4.71	0.16	4.74	0.17	4.83	0.14	4.73	0.16
5.00	0.16	5.06	0.17	5.09	0.16	5.19	0.17	5.08	0.16
5.35	0.16	5.42	0.14	5.45	0.14	5.54	0.14	5.44	0.15
5.71	0.16	5.77	0.15	5.80	0.18	5.90	0.15	5.80	0.16
6.07	0.14	6.13	0.15	6.16	0.16	6.26	0.14	6.15	0.15
6.42	0.15	6.49	0.16	6.52	0.16	6.61	0.15	6.51	0.15
6.78	0.14	6.84	0.15	6.87	0.15	6.97	0.14	6.87	0.14
7.14	0.15	7.20	0.16	7.23	0.16	7.33	0.16	7.22	0.16
7.50	0.15	7.55	0.14	7.58	0.15	7.69	0.15	7.58	0.15
7.85	0.16	7.91	0.16	7.94	0.16	8.04	0.15	7.94	0.16
8.21	0.16	8.27	0.16	8.30	0.15	8.40	0.14	8.29	0.15
8.57	0.16	8.62	0.15	8.66	0.19	8.76	0.17	8.65	0.16
8.92	0.15	8.98	0.15	9.02	0.15	9.12	0.16	9.01	0.15
9.28	0.14	9.33	0.19	9.38	0.17	9.48	0.15	9.37	0.16
9.64	0.15	9.69	0.14	9.73	0.15	9.84	0.15	9.72	0.15
9.99	0.16	10.05	0.14	10.09	0.16	10.19	0.14	10.08	0.15
10.35	0.17	10.40	0.16	10.44	0.16	10.55	0.13	10.44	0.15
10.71	0.17	10.76	0.14	10.80	0.15	10.91	0.15	10.79	0.15
11.07	0.16	11.12	0.15	11.16	0.16	11.27	0.14	11.15	0.15
11.42	0.16	11.47	0.15	11.51	0.16	11.62	0.15	11.51	0.16
11.78	0.15	11.83	0.18	11.87	0.16	11.98	0.13	11.87	0.16
12.14	0.14	12.18	0.12	12.23	0.15	12.34	0.17	12.22	0.15
12.50	0.15	12.54	0.14	12.58	0.16	12.69	0.14	12.58	0.15
12.86	0.16	12.90	0.17	12.94	0.15	13.05	0.16	12.94	0.16
13.21	0.17	13.25	0.14	13.30	0.16	13.41	0.15	13.29	0.16
13.57	0.15	13.61	0.15	13.65	0.16	13.76	0.13	13.65	0.15
13.93	0.16	13.97	0.16	14.01	0.16	14.12	0.14	14.01	0.15
14.28	0.16	14.33	0.15	14.36	0.14	14.48	0.14	14.36	0.15
14.64	0.15	14.69	0.15	14.72	0.15	14.84	0.15	14.72	0.15
15.00	0.14	15.06	0.12	15.08	0.16	15.20	0.14	15.08	0.14
15.35	0.14	15.42	0.14	15.43	0.16	15.55	0.14	15.44	0.14
15.71	0.14	15.77	0.16	15.79	0.13	15.91	0.15	15.80	0.15
16.07	0.15	16.13	0.14	16.17	0.14	16.29	0.15	16.16	0.15
16.42	0.15	16.49	0.15	16.55	0.16	16.65	0.15	16.53	0.15
16.78	0.15	16.84	0.14	16.91	0.14	17.00	0.14	16.89	0.14
17.14	0.16	17.20	0.15	17.28	0.16	17.36	0.15	17.25	0.15
17.50	0.16	17.56	0.14	17.64	0.13	17.72	0.14	17.60	0.14
17.86	0.16	17.91	0.14	18.00	0.15	18.07	0.13	17.96	0.14
18.21	0.13	18.27	0.14	18.36	0.14	18.43	0.13	18.32	0.13

18.57	0.14	18.62	0.14	18.73	0.15	18.79	0.15	18.68	0.14
18.93	0.14	18.98	0.14	19.09	0.14	19.14	0.14	19.04	0.14
19.28	0.14	19.34	0.15	19.46	0.15	19.50	0.13	19.40	0.14
19.64	0.16	19.70	0.14	19.82	0.13	19.86	0.15	19.75	0.14
20.00	0.12	20.05	0.13	20.18	0.15	20.22	0.13	20.11	0.13
<b>Average</b>	<b>0.15</b>	<b>Average</b>	<b>0.15</b>	<b>Average</b>	<b>0.14</b>	<b>Average</b>	<b>0.14</b>	<b>Average</b>	<b>0.15</b>

**Table A5: Heat Flux Results for 0.14 cal/cm<sup>2</sup>-sec Exposure.**

Insulated Copper				Embedded Thermocouple				Surface Thermocouple			
Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)
0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
0.25	0.07	0.07	0.07	0.29	0.09	0.09	0.09	0.23	0.06	0.07	0.08
0.56	0.11	0.11	0.11	0.61	0.13	0.15	0.14	0.54	0.08	0.09	0.10
0.87	0.11	0.11	0.11	0.93	0.15	0.17	0.17	0.85	0.10	0.10	0.10
1.19	0.12	0.12	0.12	1.24	0.16	0.17	0.17	1.16	0.11	0.10	0.10
1.50	0.12	0.11	0.12	1.56	0.16	0.18	0.16	1.48	0.11	0.11	0.11
1.81	0.13	0.13	0.11	1.87	0.15	0.17	0.16	1.79	0.11	0.11	0.11
2.12	0.13	0.15	0.14	2.19	0.14	0.15	0.15	2.10	0.12	0.11	0.12
2.43	0.14	0.13	0.14	2.50	0.14	0.15	0.15	2.41	0.12	0.12	0.12
2.74	0.15	0.14	0.14	2.82	0.15	0.16	0.16	2.72	0.12	0.12	0.12
3.06	0.16	0.16	0.16	3.14	0.14	0.15	0.15	3.04	0.12	0.12	0.12
3.37	0.15	0.15	0.14	3.45	0.14	0.15	0.14	3.35	0.12	0.12	0.12
3.68	0.14	0.15	0.13	3.77	0.13	0.14	0.14	3.66	0.12	0.12	0.12
3.99	0.15	0.15	0.15	4.08	0.13	0.14	0.14	3.97	0.12	0.12	0.13
4.30	0.15	0.16	0.16	4.40	0.13	0.14	0.15	4.28	0.12	0.12	0.12
4.62	0.15	0.14	0.15	4.71	0.14	0.14	0.14	4.59	0.12	0.12	0.12
4.93	0.16	0.14	0.16	5.03	0.13	0.14	0.14	4.90	0.12	0.12	0.13
5.24	0.16	0.14	0.15	5.34	0.14	0.14	0.14	5.22	0.13	0.13	0.13
5.55	0.16	0.14	0.14	5.66	0.14	0.15	0.14	5.53	0.12	0.13	0.13
5.86	0.14	0.13	0.14	5.98	0.14	0.14	0.14	5.84	0.12	0.13	0.13
6.18	0.15	0.14	0.14	6.29	0.15	0.15	0.14	6.15	0.13	0.13	0.12
6.49	0.15	0.15	0.13	6.61	0.13	0.14	0.13	6.46	0.13	0.13	0.13
6.80	0.14	0.14	0.13	6.92	0.13	0.14	0.13	6.77	0.13	0.13	0.12
7.11	0.17	0.15	0.16	7.24	0.13	0.13	0.13	7.08	0.13	0.13	0.12
7.42	0.15	0.13	0.15	7.56	0.13	0.14	0.14	7.40	0.13	0.13	0.12
7.74	0.14	0.14	0.15	7.87	0.13	0.15	0.14	7.71	0.13	0.13	0.13
8.05	0.14	0.15	0.15	8.19	0.14	0.14	0.14	8.02	0.13	0.13	0.12
8.36	0.15	0.15	0.15	8.50	0.15	0.14	0.15	8.33	0.13	0.13	0.13
8.67	0.16	0.14	0.16	8.82	0.14	0.14	0.14	8.64	0.13	0.13	0.12
8.98	0.16	0.14	0.15	9.14	0.14	0.14	0.14	8.96	0.13	0.13	0.13
9.29	0.15	0.14	0.15	9.45	0.14	0.14	0.15	9.27	0.13	0.13	0.12
9.61	0.14	0.16	0.14	9.77	0.13	0.14	0.14	9.58	0.13	0.13	0.13

9.92	0.15	0.14	0.14	10.08	0.14	0.15	0.15	9.89	0.13	0.13	0.13
10.23	0.15	0.13	0.14	10.40	0.14	0.14	0.13	10.20	0.13	0.13	0.13
10.54	0.15	0.16	0.15	10.71	0.14	0.15	0.13	10.52	0.13	0.13	0.13
10.86	0.16	0.14	0.15	11.02	0.14	0.15	0.14	10.83	0.13	0.13	0.13
11.17	0.15	0.14	0.14	11.34	0.14	0.14	0.15	11.14	0.13	0.13	0.13
11.48	0.15	0.14	0.14	11.66	0.13	0.14	0.14	11.45	0.13	0.13	0.13
11.79	0.16	0.13	0.14	11.97	0.13	0.14	0.14	11.76	0.13	0.13	0.13
12.10	0.16	0.15	0.15	12.29	0.13	0.14	0.14	12.07	0.13	0.13	0.13
12.41	0.16	0.15	0.15	12.60	0.13	0.14	0.14	12.39	0.13	0.13	0.13
12.73	0.17	0.16	0.15	12.92	0.14	0.14	0.15	12.70	0.13	0.13	0.13
13.04	0.15	0.14	0.16	13.23	0.14	0.15	0.14	13.01	0.14	0.13	0.13
13.35	0.15	0.15	0.15	13.55	0.13	0.13	0.13	13.32	0.13	0.13	0.13
13.66	0.15	0.15	0.14	13.86	0.14	0.13	0.14	13.64	0.13	0.13	0.13
13.97	0.16	0.15	0.14	14.18	0.13	0.14	0.13	13.95	0.14	0.14	0.13
14.28	0.15	0.15	0.15	14.49	0.13	0.14	0.13	14.26	0.14	0.13	0.13
14.59	0.14	0.13	0.13	14.80	0.13	0.14	0.13	14.57	0.14	0.14	0.13
14.90	0.15	0.14	0.16	15.11	0.13	0.15	0.14	14.88	0.14	0.14	0.13
15.21	0.15	0.14	0.15	15.42	0.12	0.14	0.13	15.19	0.14	0.14	0.13
15.52	0.15	0.14	0.15	15.74	0.13	0.13	0.12	15.51	0.14	0.13	0.13
15.83	0.14	0.16	0.16	16.05	0.13	0.13	0.14	15.82	0.13	0.13	0.13
16.15	0.15	0.15	0.15	16.36	0.13	0.14	0.14	16.13	0.13	0.14	0.13
16.46	0.14	0.15	0.15	16.67	0.12	0.13	0.13	16.44	0.13	0.13	0.13
16.77	0.16	0.16	0.17	16.99	0.13	0.15	0.13	16.75	0.13	0.14	0.13
17.08	0.15	0.14	0.15	17.30	0.12	0.14	0.14	17.06	0.13	0.14	0.13
17.39	0.14	0.15	0.15	17.61	0.12	0.14	0.12	17.38	0.13	0.14	0.13
17.70	0.14	0.15	0.16	17.92	0.12	0.14	0.13	17.69	0.13	0.14	0.13
18.01	0.14	0.13	0.14	18.23	0.14	0.14	0.14	18.00	0.13	0.14	0.13
18.32	0.14	0.13	0.15	18.54	0.12	0.14	0.13	18.31	0.13	0.14	0.13
18.63	0.16	0.15	0.15	18.86	0.13	0.15	0.13	18.62	0.14	0.14	0.13
18.94	0.16	0.14	0.15	19.17	0.14	0.14	0.14	18.93	0.14	0.14	0.13
19.25	0.16	0.16	0.15	19.49	0.13	0.15	0.13	19.24	0.14	0.14	0.13
19.57	0.15	0.14	0.16	19.81	0.14	0.15	0.14	19.56	0.14	0.14	0.13
19.88	0.14	0.15	0.15	20.13	0.13	0.15	0.13	19.87	0.14	0.14	0.13
20.19	0.14	0.13	0.14	20.44	0.13	0.15	0.13	20.18	0.14	0.14	0.13
<b>Avg.</b>	0.15	0.14	0.14	<b>Avg.</b>	0.14	0.14	0.14	<b>Avg.</b>	0.13	0.13	0.13

**Table A6: Sensors 1-3 Averages of Mean Heat Flux @ 0.30 cal/cm<sup>2</sup>.sec Nude Exposure.**

Embedded Thermocouple		Surface Thermocouple		Insulated Copper	
Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)
0.00	0.00	0.00	0.00	0.00	0.00
0.22	0.17	0.21	0.14	0.23	0.28

0.54	0.37	0.53	0.22	0.54	0.28
0.85	0.38	0.84	0.23	0.86	0.30
1.16	0.38	1.16	0.25	1.17	0.29
1.48	0.36	1.47	0.25	1.49	0.29
1.79	0.36	1.78	0.25	1.80	0.29
2.10	0.36	2.09	0.26	2.11	0.28
2.41	0.36	2.41	0.26	2.43	0.28
2.72	0.35	2.72	0.26	2.74	0.28
3.04	0.34	3.03	0.26	3.05	0.28
3.35	0.33	3.34	0.26	3.37	0.28
3.66	0.32	3.66	0.27	3.68	0.30
3.97	0.33	3.97	0.27	3.99	0.31
4.28	0.32	4.28	0.27	4.31	0.30
4.60	0.32	4.59	0.27	4.62	0.29
4.91	0.31	4.91	0.28	4.93	0.29
5.22	0.31	5.22	0.28	5.24	0.30
5.53	0.30	5.53	0.28	5.56	0.28
5.84	0.31	5.85	0.28	5.87	0.29
6.15	0.32	6.16	0.28	6.18	0.30
6.47	0.31	6.47	0.28	6.49	0.30
6.78	0.32	6.78	0.28	6.81	0.31
7.09	0.31	7.10	0.28	7.12	0.29
7.40	0.30	7.41	0.28	7.43	0.29
7.71	0.30	7.72	0.28	7.75	0.29
8.03	0.30	8.03	0.28	8.06	0.28
8.34	0.31	8.35	0.28	8.37	0.29
8.65	0.30	8.66	0.29	8.69	0.29
8.96	0.30	8.97	0.29	9.00	0.28
9.27	0.30	9.29	0.28	9.31	0.31
9.59	0.29	9.60	0.28	9.62	0.29
9.90	0.29	9.91	0.29	9.94	0.31
10.21	0.29	10.22	0.29	10.25	0.29
10.52	0.28	10.53	0.29	10.56	0.29
10.83	0.29	10.85	0.28	10.87	0.29
11.14	0.29	11.16	0.29	11.19	0.28
11.46	0.28	11.47	0.29	11.50	0.30
11.77	0.28	11.78	0.29	11.82	0.30
12.08	0.28	12.09	0.29	12.13	0.29
12.39	0.27	12.41	0.29	12.44	0.28
12.70	0.28	12.72	0.29	12.75	0.29
13.02	0.29	13.03	0.29	13.07	0.28
13.33	0.28	13.34	0.29	13.38	0.30
13.65	0.27	13.65	0.29	13.69	0.30
13.96	0.27	13.97	0.29	14.00	0.29
14.27	0.27	14.28	0.29	14.31	0.29
14.58	0.27	14.59	0.29	14.63	0.28

14.89	0.28	14.90	0.29	14.94	0.29
15.21	0.28	15.21	0.29	15.25	0.28
15.52	0.28	15.52	0.29	15.56	0.29
15.83	0.27	15.84	0.29	15.88	0.30
16.14	0.27	16.15	0.29	16.19	0.30
16.45	0.27	16.46	0.29	16.50	0.28
16.77	0.27	16.77	0.29	16.81	0.28
17.08	0.27	17.08	0.29	17.12	0.28
17.39	0.27	17.39	0.29	17.44	0.28
17.70	0.26	17.71	0.29	17.75	0.30
18.02	0.26	18.02	0.29	18.06	0.30
18.33	0.26	18.33	0.29	18.37	0.29
18.64	0.26	18.64	0.29	18.69	0.30
18.95	0.26	18.96	0.29	19.00	0.30
19.26	0.25	19.27	0.29	19.31	0.29
19.57	0.25	19.58	0.29	19.62	0.29
Average	0.29	Average	0.27	Average	0.29

**Table A7: TPP Heat Flux @ 0.30 cal/cm<sup>2</sup>.sec Nude Exposure.**

Trial 1		Trial 2		Trial 3		Trial 4		Average	
Time (sec)	Heat Flux (cal/cm <sup>2</sup> .s)								
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.09	0.27	0.09	0.27	0.10	0.27	0.10	0.26	0.10
0.62	0.29	0.63	0.31	0.64	0.33	0.64	0.32	0.63	0.31
0.99	0.31	1.00	0.31	1.01	0.31	1.01	0.31	1.00	0.31
1.36	0.33	1.37	0.31	1.39	0.34	1.37	0.31	1.37	0.32
1.73	0.34	1.73	0.30	1.77	0.32	1.74	0.32	1.74	0.32
2.09	0.31	2.09	0.32	2.14	0.32	2.11	0.30	2.11	0.31
2.45	0.31	2.46	0.31	2.51	0.32	2.48	0.30	2.48	0.31
2.82	0.30	2.83	0.30	2.89	0.29	2.85	0.33	2.84	0.30
3.19	0.30	3.20	0.33	3.27	0.33	3.21	0.31	3.22	0.32
3.56	0.34	3.61	0.32	3.68	0.31	3.58	0.33	3.61	0.32
3.92	0.30	4.00	0.30	4.06	0.31	3.95	0.31	3.98	0.31
4.29	0.31	4.36	0.30	4.42	0.32	4.32	0.30	4.35	0.31
4.66	0.31	4.72	0.33	4.78	0.30	4.68	0.31	4.71	0.31
5.03	0.33	5.08	0.31	5.13	0.31	5.04	0.31	5.07	0.31
5.40	0.30	5.43	0.31	5.49	0.29	5.41	0.32	5.43	0.30
5.78	0.29	5.79	0.31	5.85	0.31	5.77	0.31	5.80	0.30
6.15	0.30	6.15	0.31	6.21	0.29	6.14	0.31	6.16	0.30
6.54	0.29	6.50	0.31	6.56	0.31	6.52	0.31	6.53	0.30
6.93	0.30	6.86	0.33	6.92	0.29	6.90	0.30	6.90	0.31
7.29	0.32	7.22	0.30	7.27	0.31	7.32	0.31	7.28	0.31
7.65	0.33	7.58	0.29	7.63	0.30	7.69	0.33	7.64	0.31

8.01	0.30	7.93	0.30	7.99	0.30	8.05	0.30	7.99	0.30
8.36	0.28	8.29	0.31	8.35	0.31	8.40	0.28	8.35	0.30
8.72	0.31	8.65	0.30	8.71	0.29	8.76	0.31	8.71	0.30
9.08	0.28	9.01	0.31	9.07	0.30	9.12	0.30	9.07	0.30
9.43	0.29	9.37	0.29	9.42	0.30	9.47	0.30	9.42	0.29
9.79	0.29	9.72	0.30	9.78	0.29	9.83	0.28	9.78	0.29
10.14	0.30	10.08	0.30	10.14	0.29	10.19	0.32	10.14	0.30
10.50	0.32	10.44	0.30	10.49	0.31	10.54	0.28	10.49	0.30
10.86	0.31	10.80	0.28	10.85	0.31	10.90	0.31	10.85	0.30
11.22	0.30	11.16	0.32	11.21	0.29	11.26	0.29	11.21	0.30
11.57	0.28	11.51	0.30	11.57	0.30	11.61	0.30	11.57	0.30
11.93	0.30	11.87	0.30	11.92	0.31	11.97	0.29	11.92	0.30
12.29	0.29	12.23	0.28	12.28	0.28	12.33	0.28	12.28	0.29
12.64	0.34	12.58	0.29	12.64	0.29	12.69	0.31	12.64	0.31
13.00	0.30	12.94	0.31	12.99	0.29	13.05	0.28	13.00	0.30
13.36	0.30	13.30	0.28	13.35	0.28	13.41	0.28	13.35	0.28
13.72	0.27	13.66	0.29	13.71	0.28	13.77	0.27	13.71	0.27
14.07	0.28	14.02	0.27	14.07	0.27	14.12	0.28	14.07	0.28
14.43	0.30	14.37	0.28	14.43	0.29	14.48	0.27	14.43	0.28
14.79	0.29	14.73	0.25	14.78	0.26	14.84	0.28	14.78	0.27
15.14	0.29	15.08	0.28	15.14	0.27	15.19	0.25	15.14	0.27
15.50	0.27	15.44	0.26	15.50	0.27	15.55	0.27	15.50	0.27
15.86	0.31	15.80	0.25	15.85	0.27	15.91	0.28	15.85	0.28
16.21	0.29	16.15	0.28	16.21	0.26	16.27	0.26	16.21	0.27
16.57	0.29	16.51	0.27	16.57	0.29	16.62	0.27	16.57	0.28
16.93	0.27	16.87	0.26	16.92	0.27	16.98	0.28	16.92	0.27
17.28	0.27	17.22	0.27	17.28	0.26	17.34	0.27	17.28	0.27
17.64	0.27	17.58	0.28	17.64	0.26	17.70	0.28	17.64	0.27
18.00	0.27	17.94	0.27	18.00	0.27	18.06	0.26	18.00	0.27
18.36	0.28	18.29	0.26	18.35	0.27	18.41	0.27	18.35	0.27
18.71	0.27	18.65	0.28	18.71	0.25	18.77	0.28	18.71	0.27
19.07	0.29	19.02	0.28	19.07	0.27	19.13	0.27	19.07	0.28
19.43	0.27	19.37	0.25	19.43	0.25	19.48	0.26	19.43	0.26
19.78	0.28	19.73	0.27	19.79	0.27	19.84	0.25	19.79	0.27
20.03	0.29	19.98	0.31	20.01	0.27	20.06	0.26	20.02	0.28
<b>Avg.</b>	0.29	<b>Avg.</b>	0.30	<b>Avg.</b>	0.29	<b>Avg.</b>	0.30	<b>Avg.</b>	0.30

**Table A8: Heat Flux Results for 0.30 cal/cm<sup>2</sup>·sec Exposure.**

Insulated Copper				Embedded Thermocouple				Surface Thermocouple			
Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.23	0.28	0.28	0.28	0.22	0.17	0.18	0.17	0.21	0.15	0.12	0.16
0.54	0.28	0.27	0.27	0.54	0.33	0.39	0.39	0.53	0.22	0.19	0.24

0.86	0.31	0.29	0.32	0.85	0.36	0.38	0.40	0.84	0.24	0.21	0.25
1.18	0.29	0.28	0.29	1.16	0.34	0.39	0.40	1.16	0.25	0.22	0.26
1.49	0.30	0.28	0.30	1.48	0.33	0.37	0.37	1.47	0.27	0.23	0.26
1.80	0.30	0.28	0.29	1.79	0.34	0.37	0.36	1.78	0.27	0.23	0.26
2.11	0.28	0.27	0.28	2.10	0.34	0.36	0.37	2.09	0.27	0.24	0.26
2.43	0.28	0.27	0.28	2.41	0.34	0.36	0.37	2.41	0.28	0.24	0.27
2.74	0.28	0.28	0.28	2.72	0.33	0.37	0.35	2.72	0.28	0.24	0.26
3.06	0.29	0.27	0.29	3.04	0.33	0.35	0.36	3.03	0.28	0.24	0.26
3.37	0.28	0.27	0.29	3.35	0.31	0.34	0.34	3.34	0.28	0.24	0.26
3.68	0.31	0.28	0.30	3.66	0.32	0.32	0.31	3.66	0.29	0.25	0.26
3.99	0.30	0.30	0.31	3.97	0.32	0.32	0.34	3.97	0.29	0.26	0.27
4.30	0.31	0.29	0.30	4.28	0.30	0.33	0.32	4.28	0.29	0.26	0.27
4.62	0.30	0.28	0.29	4.60	0.31	0.33	0.30	4.59	0.29	0.25	0.27
4.93	0.31	0.27	0.30	4.91	0.31	0.32	0.30	4.91	0.30	0.26	0.28
5.24	0.32	0.28	0.29	5.22	0.30	0.33	0.30	5.22	0.30	0.26	0.27
5.55	0.30	0.27	0.28	5.53	0.29	0.32	0.29	5.53	0.30	0.26	0.28
5.87	0.30	0.28	0.28	5.84	0.31	0.32	0.31	5.85	0.30	0.26	0.28
6.18	0.31	0.28	0.29	6.15	0.31	0.32	0.32	6.16	0.30	0.27	0.28
6.49	0.31	0.30	0.28	6.47	0.30	0.32	0.32	6.47	0.30	0.26	0.28
6.81	0.32	0.30	0.30	6.78	0.31	0.34	0.30	6.78	0.30	0.26	0.28
7.12	0.30	0.28	0.29	7.09	0.29	0.33	0.30	7.10	0.30	0.27	0.28
7.43	0.30	0.28	0.29	7.40	0.29	0.31	0.29	7.41	0.30	0.26	0.27
7.74	0.29	0.28	0.30	7.71	0.29	0.32	0.29	7.72	0.30	0.27	0.27
8.06	0.29	0.27	0.28	8.03	0.29	0.32	0.30	8.03	0.30	0.27	0.28
8.37	0.30	0.27	0.30	8.34	0.29	0.32	0.31	8.35	0.30	0.27	0.28
8.68	0.30	0.29	0.28	8.65	0.29	0.31	0.30	8.66	0.30	0.27	0.28
8.99	0.29	0.27	0.28	8.96	0.30	0.30	0.30	8.97	0.30	0.27	0.28
9.30	0.31	0.30	0.30	9.27	0.29	0.30	0.31	9.29	0.30	0.27	0.28
9.62	0.30	0.28	0.29	9.59	0.28	0.29	0.30	9.60	0.30	0.27	0.28
9.93	0.31	0.30	0.31	9.90	0.28	0.29	0.29	9.91	0.30	0.27	0.28
10.24	0.30	0.28	0.29	10.21	0.28	0.29	0.29	10.22	0.30	0.27	0.28
10.55	0.30	0.28	0.28	10.52	0.28	0.29	0.29	10.53	0.30	0.27	0.28
10.87	0.30	0.28	0.29	10.83	0.28	0.30	0.30	10.85	0.30	0.27	0.28
11.18	0.29	0.28	0.28	11.14	0.29	0.29	0.30	11.16	0.30	0.27	0.28
11.50	0.30	0.30	0.29	11.46	0.28	0.28	0.28	11.47	0.30	0.28	0.29
11.81	0.29	0.30	0.30	11.77	0.27	0.28	0.27	11.78	0.30	0.27	0.29
12.12	0.30	0.29	0.29	12.08	0.29	0.28	0.27	12.09	0.30	0.28	0.29
12.44	0.28	0.29	0.29	12.39	0.28	0.27	0.27	12.41	0.30	0.27	0.29
12.75	0.28	0.29	0.29	12.70	0.28	0.28	0.27	12.72	0.31	0.27	0.29
13.06	0.27	0.28	0.28	13.02	0.28	0.31	0.27	13.03	0.31	0.28	0.29
13.37	0.30	0.30	0.30	13.33	0.27	0.30	0.27	13.34	0.31	0.28	0.29
13.69	0.30	0.30	0.30	13.65	0.27	0.28	0.26	13.65	0.31	0.28	0.29
14.00	0.31	0.26	0.30	13.96	0.27	0.28	0.26	13.97	0.31	0.28	0.29
14.31	0.29	0.28	0.29	14.27	0.26	0.28	0.26	14.28	0.30	0.27	0.29
14.62	0.29	0.27	0.28	14.58	0.26	0.28	0.27	14.59	0.30	0.27	0.28

14.94	0.30	0.28	0.29	14.89	0.27	0.29	0.28	14.90	0.30	0.27	0.28
15.25	0.29	0.26	0.28	15.21	0.28	0.30	0.28	15.21	0.30	0.27	0.29
15.56	0.30	0.27	0.29	15.52	0.28	0.29	0.27	15.52	0.30	0.27	0.28
15.87	0.31	0.28	0.30	15.83	0.29	0.26	0.26	15.84	0.31	0.27	0.28
16.19	0.30	0.28	0.30	16.14	0.27	0.27	0.26	16.15	0.31	0.28	0.28
16.50	0.29	0.28	0.28	16.45	0.27	0.26	0.28	16.46	0.31	0.28	0.28
16.81	0.29	0.27	0.29	16.77	0.26	0.27	0.27	16.77	0.31	0.27	0.28
17.12	0.29	0.28	0.28	17.08	0.26	0.28	0.26	17.08	0.30	0.28	0.28
17.43	0.28	0.27	0.29	17.39	0.27	0.27	0.28	17.39	0.31	0.27	0.28
17.75	0.32	0.29	0.29	17.70	0.26	0.27	0.26	17.71	0.31	0.27	0.28
18.06	0.31	0.29	0.30	18.02	0.26	0.27	0.25	18.02	0.31	0.27	0.28
18.37	0.30	0.28	0.28	18.33	0.26	0.27	0.25	18.33	0.31	0.28	0.28
18.68	0.30	0.29	0.30	18.64	0.26	0.26	0.25	18.64	0.31	0.28	0.28
19.00	0.30	0.30	0.29	18.95	0.26	0.26	0.24	18.96	0.30	0.28	0.28
19.31	0.30	0.28	0.29	19.26	0.25	0.25	0.24	19.27	0.31	0.28	0.28
19.62	0.30	0.27	0.29	19.57	0.25	0.25	0.24	19.58	0.31	0.28	0.28
<b>Avg.</b>	0.30	0.28	0.29	<b>Avg.</b>	0.29	0.31	0.30	<b>Avg.</b>	0.30	0.26	0.28

**Table A9: Sensors 1-3 Averages of Mean Heat Flux @ 2.00 cal/cm<sup>2</sup>.sec Nude Exposure.**

Embedded Thermocouple		Surface Thermocouple		Insulated Copper	
Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)
0.00	0.12	0.00	0.06	0.00	0.36
0.06	0.43	0.06	0.18	0.06	1.17
0.12	1.03	0.12	0.33	0.13	2.05
0.19	1.67	0.19	0.46	0.19	2.44
0.25	2.05	0.25	0.55	0.25	2.44
0.31	2.20	0.31	0.62	0.31	2.37
0.37	2.22	0.37	0.68	0.38	2.31
0.44	2.17	0.44	0.73	0.44	2.32
0.50	2.19	0.50	0.78	0.50	2.28
0.56	2.18	0.56	0.83	0.56	2.27
0.62	2.17	0.62	0.87	0.63	2.31
0.69	2.16	0.68	0.91	0.69	2.27
0.75	2.11	0.75	0.95	0.75	2.25
0.81	2.11	0.81	0.98	0.81	2.23
0.87	2.08	0.87	1.00	0.88	2.20
0.93	2.05	0.93	1.03	0.94	2.16
1.00	2.02	0.99	1.05	1.00	2.15
1.06	2.01	1.06	1.08	1.06	2.13
1.12	2.01	1.12	1.10	1.12	2.16
1.18	2.01	1.18	1.12	1.19	2.15

1.25	1.99	1.24	1.14	1.25	2.13
1.31	1.98	1.31	1.16	1.31	2.09
1.37	1.95	1.37	1.18	1.37	2.02
1.43	1.93	1.43	1.20	1.44	1.97
1.50	1.93	1.49	1.22	1.50	1.91
1.56	1.91	1.56	1.23	1.56	1.91
1.62	1.89	1.62	1.24	1.62	1.83
1.68	1.86	1.68	1.26	1.69	1.81
1.75	1.84	1.74	1.27	1.75	1.82
1.81	1.82	1.81	1.29	1.81	1.82
1.87	1.82	1.87	1.30	1.87	1.80
1.93	1.82	1.93	1.31	1.94	1.79
2.00	1.78	1.99	1.32	2.00	1.78
2.06	1.79	2.06	1.33	2.06	1.77
2.12	1.79	2.12	1.34	2.12	1.78
2.18	1.79	2.18	1.35	2.18	1.78
2.25	1.77	2.24	1.36	2.25	1.81
2.31	1.75	2.30	1.36	2.31	1.80
2.37	1.74	2.37	1.37	2.37	1.84
2.43	1.73	2.43	1.38	2.43	1.86
2.50	1.73	2.49	1.39	2.50	1.90
2.56	1.72	2.55	1.40	2.56	1.94
2.62	1.71	2.61	1.41	2.62	1.94
2.68	1.72	2.68	1.41	2.68	1.97
2.75	1.70	2.74	1.42	2.75	2.01
2.81	1.69	2.80	1.43	2.81	2.02
2.87	1.69	2.86	1.43	2.87	2.03
2.93	1.68	2.93	1.44	2.93	2.01
3.00	1.68	2.99	1.45	3.00	2.02
3.06	1.66	3.05	1.45	3.06	1.98
3.12	1.65	3.11	1.45	3.12	1.99
3.18	1.65	3.18	1.46	3.18	2.03
3.25	1.64	3.24	1.46	3.25	2.04
3.31	1.57	3.30	1.46	3.31	2.06
3.37	1.39	3.36	1.47	3.37	2.06
3.43	1.31	3.42	1.48	3.43	2.02
		3.49	1.48	3.49	2.02
		3.55	1.49	3.56	2.02
		3.61	1.49	3.62	2.04
		3.67	1.49	3.68	2.03
		3.74	1.50	3.74	2.03
		3.80	1.50	3.81	2.03
		3.86	1.51	3.87	2.00
		3.92	1.51	3.93	1.98
		3.98	1.51	3.99	1.97
		4.05	1.52	4.05	1.98

		4.11	1.52	4.12	1.97
		4.17	1.53	4.18	1.97
		4.23	1.53	4.24	2.00
		4.30	1.53	4.31	1.94
		4.36	1.54	4.37	1.95
		4.42	1.54	4.43	1.96
		4.48	1.54	4.49	1.94
		4.55	1.55	4.56	1.98
		4.61	1.55	4.62	2.00
		4.67	1.55	4.68	1.99
		4.73	1.56	4.74	2.00
		4.79	1.56	4.80	1.96
		4.86	1.56	4.87	1.98
		4.92	1.56	4.93	1.96
		4.98	1.56	4.99	1.97
		5.04	1.57	5.05	1.96
		5.11	1.57	5.12	1.94
		5.17	1.57	5.18	1.99
		5.23	1.57	5.24	2.02
		5.29	1.57	5.30	1.97
		5.35	1.57	5.37	1.98
		5.42	1.58	5.43	1.97
		5.48	1.58	5.49	2.02
		5.54	1.58	5.55	1.98
		5.60	1.57	5.61	1.82
		5.66	1.55	5.68	1.65
		5.73	1.52	5.74	1.51
		5.79	1.49	5.80	1.40
Average	1.88	Average	1.30	Average	1.97

**Table A10: TPP Heat Flux @ 2.00 cal/cm<sup>2</sup>.sec Nude Exposure.**

Trial 1		Trial 2		Trial 3		Trial 4		Average	
Time	Flux								
0.03	0.30	0.00	2.24	0.00	2.27	0.00	2.31	0.00	0.11
0.12	0.25	0.12	2.05	0.12	2.02	0.12	2.04	0.07	0.57
0.20	0.01	0.20	0.02	0.20	0.05	0.20	0.03	0.15	1.86
0.27	0.08	0.27	0.07	0.27	0.02	0.27	0.06	0.22	2.43
0.34	0.13	0.34	0.05	0.34	0.11	0.34	0.15	0.29	2.64
0.41	0.40	0.42	0.80	0.42	0.43	0.41	0.63	0.37	2.59
0.49	1.68	0.49	2.16	0.49	1.67	0.49	1.93	0.44	2.55
0.56	2.40	0.56	2.52	0.56	2.35	0.56	2.45	0.52	2.45
0.64	2.77	0.63	2.59	0.64	2.70	0.64	2.48	0.59	2.51
0.71	2.77	0.71	2.62	0.71	2.63	0.71	2.34	0.67	2.51
0.79	2.71	0.79	2.48	0.79	2.59	0.78	2.44	0.74	2.49

0.86	2.50	0.86	2.45	0.86	2.54	0.86	2.30	0.82	2.47
0.93	2.68	0.93	2.43	0.93	2.62	0.93	2.30	0.89	2.40
1.01	2.72	1.01	2.49	1.00	2.55	1.01	2.29	0.97	2.48
1.08	2.51	1.09	2.49	1.08	2.51	1.08	2.44	1.04	2.30
1.16	2.55	1.16	2.37	1.15	2.58	1.16	2.39	1.12	2.20
1.23	2.42	1.24	2.32	1.23	2.48	1.23	2.38	1.19	2.29
1.31	2.60	1.31	2.29	1.31	2.61	1.31	2.40	1.27	2.29
1.38	2.41	1.39	2.29	1.38	2.11	1.38	2.38	1.34	2.21
1.46	2.21	1.46	2.23	1.46	2.10	1.46	2.26	1.42	2.14
1.53	2.28	1.54	2.23	1.53	2.43	1.54	2.21	1.49	2.10
1.61	2.23	1.61	2.41	1.60	2.47	1.61	2.07	1.57	2.09
1.68	2.18	1.69	2.28	1.68	2.25	1.69	2.12	1.64	2.04
1.76	1.89	1.76	2.28	1.76	2.26	1.77	2.12	1.72	1.95
1.83	1.95	1.83	2.19	1.83	2.19	1.84	2.08	1.79	1.90
1.91	2.06	1.91	2.15	1.91	2.01	1.91	2.14	1.86	1.91
1.98	1.96	1.98	2.08	1.98	2.11	1.99	2.01	1.94	1.88
2.05	1.89	2.06	2.03	2.06	1.99	2.06	1.89	2.01	1.85
2.13	1.95	2.13	1.97	2.13	1.84	2.14	1.82	2.09	1.78
2.20	2.04	2.21	2.01	2.21	1.87	2.22	1.72	2.18	1.73
2.27	1.98	2.28	1.94	2.28	1.81	2.29	1.78	2.26	1.80
2.35	1.92	2.36	1.88	2.35	1.86	2.37	1.75	2.33	1.85
2.42	1.74	2.43	1.83	2.45	1.88	2.44	1.69	2.41	1.88
2.54	1.83	2.50	1.62	2.54	1.74	2.52	1.74	2.49	1.94
2.61	1.88	2.58	1.69	2.63	1.81	2.59	1.81	2.57	2.01
2.69	1.94	2.65	1.82	2.70	1.93	2.66	1.70	2.64	2.00
2.76	2.04	2.72	1.92	2.77	1.95	2.74	1.62	2.71	2.04
2.83	2.16	2.83	1.94	2.84	2.04	2.81	1.64	2.78	2.08
2.91	2.26	2.93	1.89	2.92	2.15	2.88	1.75	2.85	2.15
2.98	2.19	3.00	2.06	2.99	2.06	2.95	1.70	2.93	2.10
3.05	2.13	3.07	2.10	3.06	2.00	3.03	1.94	3.00	2.11
3.12	2.22	3.14	2.12	3.13	2.15	3.10	1.85	3.07	2.12
3.19	2.30	3.21	2.21	3.20	2.14	3.18	1.95	3.14	2.11
3.26	2.26	3.29	2.15	3.28	2.11	3.25	1.88	3.22	2.11
3.34	2.10	3.36	2.15	3.35	2.10	3.32	2.08	3.29	2.10
3.41	2.03	3.43	2.20	3.42	2.18	3.40	2.07	3.36	2.10
3.48	2.11	3.50	2.20	3.49	2.16	3.48	1.96	3.43	2.08
3.55	2.15	3.57	2.23	3.56	2.16	3.55	1.90	3.50	2.10
3.62	2.21	3.65	2.11	3.63	2.17	3.62	1.91	3.58	2.13
3.69	2.10	3.72	2.17	3.70	2.14	3.70	1.99	3.65	2.11
3.77	2.04	3.79	2.09	3.77	2.14	3.77	2.05	3.72	2.09
3.84	2.12	3.86	2.13	3.84	2.13	3.84	2.02	3.79	2.10
3.91	2.27	3.93	2.17	3.92	2.02	3.92	2.08	3.86	2.15
3.98	2.20	4.00	2.11	3.99	2.10	3.99	2.04	3.94	2.11
4.05	2.18	4.07	2.07	4.06	2.14	4.06	1.95	4.01	2.07
4.12	2.18	4.15	2.19	4.13	2.12	4.14	1.93	4.08	2.08

4.19	2.15	4.22	2.24	4.20	2.13	4.21	2.08	4.15	2.09
4.27	2.02	4.29	2.17	4.27	2.14	4.29	2.13	4.22	2.14
4.34	2.08	4.36	2.17	4.35	2.06	4.36	1.96	4.30	2.05
4.41	2.12	4.43	2.20	4.42	2.08	4.43	1.92	4.37	2.10
4.48	2.22	4.50	2.15	4.49	2.11	4.50	1.88	4.45	2.15
4.55	2.21	4.57	2.19	4.56	2.08	4.58	2.05	4.52	2.09
4.62	2.14	4.65	2.07	4.63	2.00	4.66	1.98	4.60	2.06
4.69	2.11	4.72	2.21	4.70	2.04	4.75	2.03	4.67	2.12
4.77	2.15	4.79	2.25	4.77	2.19	4.84	2.01	4.71	2.16
4.84	2.07	4.86	2.17	4.85	2.13	4.93	1.99	4.87	2.09
4.91	1.97	4.93	2.13	4.92	2.10	5.00	2.05	4.94	2.06
4.98	2.11	5.00	2.20	4.99	2.10	5.07	2.09	5.01	2.12
Average	2.00	Average	2.05	Average	2.04	Average	1.93	Average	2.01

Table A11: Heat Flux Results for 2.00 cal/cm<sup>2</sup>sec Exposure.

Insulated Copper				Embedded Thermocouple				Surface Thermocouple			
Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)	Time (sec.)	Flux 1 (cal/cm <sup>2</sup> s)	Flux 2 (cal/cm <sup>2</sup> s)	Flux 3 (cal/cm <sup>2</sup> s)
0.00	0.32	0.40	0.35	0.00	0.09	0.08	0.19	0.00	0.06	0.06	0.06
0.06	1.13	1.21	1.16	0.06	0.40	0.37	0.51	0.06	0.18	0.18	0.17
0.13	2.12	2.01	2.02	0.12	1.01	1.04	1.05	0.12	0.33	0.33	0.34
0.19	2.53	2.37	2.43	0.19	1.57	1.81	1.63	0.19	0.46	0.45	0.48
0.25	2.48	2.38	2.45	0.25	1.84	2.27	2.04	0.25	0.55	0.53	0.58
0.31	2.40	2.34	2.37	0.31	1.92	2.41	2.27	0.31	0.61	0.59	0.66
0.38	2.36	2.28	2.28	0.37	1.95	2.40	2.32	0.37	0.66	0.64	0.73
0.44	2.38	2.26	2.32	0.44	1.87	2.38	2.27	0.44	0.72	0.69	0.79
0.50	2.32	2.19	2.33	0.50	1.89	2.41	2.27	0.50	0.77	0.73	0.84
0.56	2.30	2.18	2.34	0.56	1.89	2.38	2.26	0.56	0.82	0.78	0.89
0.63	2.35	2.24	2.33	0.62	1.89	2.37	2.26	0.62	0.87	0.82	0.92
0.69	2.30	2.25	2.25	0.69	1.88	2.37	2.23	0.68	0.91	0.86	0.96
0.75	2.28	2.27	2.21	0.75	1.87	2.29	2.17	0.75	0.95	0.89	1.00
0.81	2.27	2.25	2.18	0.81	1.92	2.24	2.18	0.81	0.99	0.92	1.03
0.88	2.29	2.21	2.10	0.87	1.91	2.20	2.12	0.87	1.02	0.94	1.05
0.94	2.29	2.14	2.06	0.93	1.90	2.14	2.11	0.93	1.05	0.96	1.07
1.00	2.29	2.11	2.04	1.00	1.87	2.10	2.10	0.99	1.08	0.98	1.10
1.06	2.27	2.09	2.04	1.06	1.84	2.07	2.11	1.06	1.10	1.01	1.12
1.12	2.25	2.13	2.09	1.12	1.85	2.08	2.10	1.12	1.13	1.03	1.14
1.19	2.21	2.12	2.10	1.18	1.83	2.09	2.10	1.18	1.15	1.06	1.15
1.25	2.19	2.10	2.09	1.25	1.82	2.08	2.08	1.24	1.17	1.08	1.18
1.31	2.11	2.10	2.04	1.31	1.80	2.05	2.08	1.31	1.20	1.09	1.20
1.37	2.06	2.03	1.97	1.37	1.79	2.00	2.07	1.37	1.22	1.11	1.22
1.44	2.03	1.93	1.94	1.43	1.78	1.97	2.04	1.43	1.24	1.12	1.24
1.50	1.98	1.85	1.92	1.50	1.80	1.97	2.00	1.49	1.25	1.14	1.26
1.56	1.99	1.82	1.92	1.56	1.81	1.96	1.96	1.56	1.27	1.15	1.27

1.62	1.94	1.75	1.79	1.62	1.81	1.92	1.93	1.62	1.29	1.16	1.29
1.69	1.97	1.73	1.73	1.68	1.78	1.89	1.91	1.68	1.30	1.17	1.30
1.75	1.97	1.73	1.77	1.75	1.75	1.88	1.90	1.74	1.32	1.18	1.32
1.81	1.96	1.73	1.76	1.81	1.72	1.85	1.90	1.81	1.33	1.20	1.33
1.87	1.96	1.72	1.71	1.87	1.70	1.84	1.91	1.87	1.35	1.21	1.34
1.94	1.98	1.71	1.68	1.93	1.72	1.87	1.85	1.93	1.36	1.23	1.35
2.00	1.94	1.71	1.69	2.00	1.67	1.82	1.86	1.99	1.37	1.24	1.35
2.06	1.92	1.72	1.67	2.06	1.69	1.83	1.85	2.06	1.38	1.25	1.36
2.12	1.95	1.74	1.67	2.12	1.69	1.84	1.85	2.12	1.39	1.26	1.37
2.18	1.93	1.73	1.67	2.18	1.69	1.84	1.85	2.18	1.40	1.26	1.39
2.25	1.95	1.75	1.72	2.25	1.67	1.81	1.82	2.24	1.40	1.27	1.40
2.31	1.92	1.73	1.74	2.31	1.66	1.80	1.80	2.30	1.41	1.28	1.41
2.37	1.96	1.80	1.77	2.37	1.65	1.80	1.76	2.37	1.42	1.29	1.41
2.43	1.99	1.86	1.75	2.43	1.64	1.78	1.76	2.43	1.43	1.30	1.42
2.50	2.03	1.87	1.80	2.50	1.64	1.78	1.77	2.49	1.44	1.30	1.43
2.56	2.06	1.89	1.87	2.56	1.64	1.75	1.76	2.55	1.45	1.31	1.44
2.62	2.03	1.92	1.87	2.62	1.64	1.75	1.75	2.61	1.46	1.32	1.44
2.68	2.05	1.96	1.89	2.68	1.65	1.77	1.75	2.68	1.46	1.33	1.45
2.75	2.09	2.02	1.92	2.75	1.64	1.76	1.71	2.74	1.47	1.34	1.45
2.81	2.10	2.02	1.94	2.81	1.63	1.75	1.71	2.80	1.48	1.34	1.46
2.87	2.12	2.01	1.95	2.87	1.64	1.74	1.70	2.86	1.49	1.35	1.46
2.93	2.10	1.99	1.96	2.93	1.62	1.73	1.70	2.93	1.49	1.36	1.47
3.00	2.11	2.02	1.94	3.00	1.60	1.73	1.70	2.99	1.50	1.37	1.47
3.06	2.07	1.99	1.87	3.06	1.58	1.72	1.69	3.05	1.50	1.37	1.48
3.12	2.08	2.01	1.87	3.12	1.56	1.70	1.69	3.11	1.51	1.38	1.48
3.18	2.12	2.07	1.89	3.18	1.57	1.70	1.69	3.18	1.51	1.38	1.49
3.25	2.11	2.07	1.93	3.25	1.57	1.67	1.68	3.24	1.51	1.38	1.49
3.31	2.12	2.06	1.99	3.31	1.57	1.48	1.67	3.30	1.52	1.38	1.50
3.37	2.11	2.04	2.02					3.36	1.52	1.39	1.50
3.43	2.06	1.99	2.02					3.42	1.52	1.40	1.51
3.49	2.06	2.00	2.02					3.49	1.53	1.40	1.51
3.56	2.04	1.99	2.02					3.55	1.54	1.41	1.51
3.62	2.09	2.00	2.03					3.61	1.54	1.41	1.52
3.68	2.10	2.03	1.98					3.67	1.55	1.42	1.52
3.74	2.11	2.03	1.95					3.74	1.55	1.42	1.52
3.81	2.11	2.01	1.97					3.80	1.56	1.43	1.53
3.87	2.09	1.99	1.92					3.86	1.56	1.43	1.53
3.93	2.07	1.98	1.90					3.92	1.56	1.43	1.53
3.99	2.03	1.99	1.90					3.98	1.57	1.43	1.54
4.05	2.03	2.01	1.90					4.05	1.57	1.44	1.54
4.12	2.03	1.98	1.88					4.11	1.58	1.45	1.54
4.18	2.05	1.95	1.91					4.17	1.59	1.45	1.54
4.24	2.09	1.92	1.99					4.23	1.59	1.46	1.55
4.31	2.03	1.86	1.94					4.30	1.59	1.46	1.55
4.37	2.04	1.88	1.93					4.36	1.59	1.46	1.56
4.43	2.03	1.94	1.92					4.42	1.60	1.46	1.56

4.49	2.01	1.93	1.89					4.48	1.60	1.47	1.56
4.56	2.07	1.95	1.92					4.55	1.60	1.47	1.56
4.62	2.10	1.96	1.94					4.61	1.60	1.48	1.56
4.68	2.06	1.95	1.96					4.67	1.61	1.48	1.57
4.74	2.05	1.98	1.98					4.73	1.61	1.48	1.57
4.80	2.01	1.95	1.93					4.79	1.61	1.49	1.57
4.87	2.04	1.95	1.94					4.86	1.62	1.49	1.58
4.93	2.03	1.94	1.92					4.92	1.62	1.49	1.58
4.99	2.03	1.96	1.92					4.98	1.62	1.49	1.58
5.05	2.00	1.93	1.94					5.04	1.62	1.49	1.59
5.12	1.99	1.92	1.92					5.11	1.62	1.49	1.59
5.18	2.06	1.96	1.95					5.17	1.63	1.49	1.59
5.24	2.08	1.99	1.98					5.23	1.63	1.49	1.59
5.30	2.02	1.94	1.96					5.29	1.63	1.49	1.59
5.37	2.04	1.97	1.92					5.35	1.63	1.50	1.59
5.43	1.99	1.96	1.97					5.42	1.64	1.51	1.59
5.49	2.05	2.01	1.99					5.48	1.64	1.51	1.59
5.55	2.05	1.98	1.90					5.54	1.64	1.51	1.59
5.61	1.89	1.82	1.75					5.60	1.63	1.50	1.58
5.68	1.69	1.65	1.60					5.66	1.61	1.47	1.56
5.74	1.54	1.51	1.46					5.73	1.58	1.45	1.53
5.80	1.46	1.39	1.36					5.79	1.56	1.42	1.50
<b>Avg.</b>	2.10	1.99	1.96	<b>Avg.</b>	1.74	1.96	1.93	<b>Avg.</b>	1.33	1.22	1.33

**Table A12: Heat Flux Results for 2.00 cal/cm<sup>2</sup>-sec Covered Exposure.**

Flame Retardant Cotton				Nomex® III				Wool			
Time (sec.)	Insulated Copper Flux (cal/cm <sup>2</sup> s)	Embedded Thermocouple Flux (cal/cm <sup>2</sup> s)	Surface Thermocouple Flux (cal/cm <sup>2</sup> s)	Time (sec.)	Insulated Copper Flux (cal/cm <sup>2</sup> s)	Embedded Thermocouple Flux (cal/cm <sup>2</sup> s)	Surface Thermocouple Flux (cal/cm <sup>2</sup> s)	Time (sec.)	Insulated Copper Flux (cal/cm <sup>2</sup> s)	Embedded Thermocouple Flux (cal/cm <sup>2</sup> s)	Surface Thermocouple Flux (cal/cm <sup>2</sup> s)
0.00	0.07	0.02	0.00	0.00	0.03	0.02	0.00	0.00	0.06	0.02	0.01
0.06	0.07	0.02	0.00	0.06	0.05	0.03	0.00	0.06	0.04	0.02	0.01
0.12	0.07	0.02	0.00	0.12	0.06	0.02	0.00	0.12	0.05	0.03	0.01
0.18	0.07	0.02	0.00	0.18	0.08	0.02	0.00	0.19	0.07	0.03	0.01
0.25	0.11	0.02	0.00	0.25	0.06	0.03	0.00	0.25	0.09	0.02	0.02
0.31	0.08	0.03	0.00	0.31	0.11	0.04	0.00	0.31	0.07	0.03	0.02
0.37	0.09	0.04	0.01	0.37	0.06	0.04	0.00	0.37	0.06	0.03	0.02
0.43	0.10	0.04	0.01	0.43	0.11	0.05	0.01	0.43	0.08	0.04	0.03
0.49	0.07	0.04	0.01	0.49	0.09	0.06	0.01	0.49	0.12	0.03	0.03
0.56	0.11	0.04	0.01	0.56	0.09	0.06	0.01	0.56	0.09	0.04	0.04
0.62	0.12	0.05	0.01	0.62	0.11	0.07	0.01	0.62	0.11	0.04	0.04
0.68	0.12	0.05	0.01	0.68	0.11	0.07	0.01	0.68	0.14	0.04	0.04
0.75	0.11	0.05	0.01	0.74	0.13	0.08	0.01	0.74	0.12	0.05	0.04
0.81	0.14	0.06	0.02	0.81	0.12	0.08	0.01	0.80	0.14	0.06	0.04
0.87	0.15	0.06	0.02	0.87	0.14	0.09	0.02	0.87	0.16	0.07	0.05

0.93	0.15	0.07	0.02	0.93	0.17	0.10	0.02	0.93	0.20	0.08	0.05
0.99	0.17	0.08	0.03	0.99	0.16	0.11	0.02	0.99	0.17	0.09	0.06
1.06	0.21	0.10	0.03	1.05	0.18	0.13	0.03	1.05	0.21	0.10	0.06
1.12	0.20	0.11	0.04	1.12	0.19	0.13	0.03	1.11	0.19	0.11	0.07
1.18	0.21	0.12	0.04	1.18	0.19	0.14	0.03	1.17	0.20	0.11	0.07
1.24	0.24	0.13	0.05	1.24	0.18	0.15	0.04	1.24	0.23	0.12	0.08
1.31	0.27	0.14	0.05	1.30	0.23	0.17	0.04	1.30	0.24	0.13	0.08
1.37	0.28	0.16	0.06	1.36	0.24	0.18	0.04	1.36	0.25	0.14	0.09
1.43	0.28	0.17	0.06	1.43	0.21	0.18	0.05	1.42	0.24	0.14	0.09
1.49	0.29	0.18	0.07	1.49	0.23	0.18	0.05	1.48	0.28	0.15	0.09
1.55	0.27	0.19	0.07	1.55	0.23	0.19	0.05	1.55	0.28	0.16	0.10
1.62	0.28	0.19	0.07	1.61	0.23	0.19	0.05	1.61	0.27	0.17	0.10
1.68	0.29	0.19	0.07	1.67	0.24	0.20	0.05	1.67	0.31	0.16	0.10
1.74	0.28	0.20	0.07	1.74	0.23	0.20	0.06	1.74	0.33	0.17	0.11
1.80	0.27	0.20	0.08	1.80	0.21	0.20	0.06	1.80	0.31	0.18	0.11
1.86	0.28	0.20	0.08	1.86	0.24	0.20	0.06	1.86	0.33	0.18	0.11
1.93	0.26	0.20	0.08	1.92	0.24	0.20	0.06	1.92	0.34	0.19	0.11
1.99	0.27	0.19	0.08	1.99	0.25	0.20	0.06	1.99	0.34	0.19	0.11
2.05	0.28	0.19	0.08	2.05	0.25	0.21	0.07	2.05	0.35	0.19	0.12
2.11	0.30	0.19	0.08	2.11	0.25	0.21	0.07	2.11	0.34	0.19	0.12
2.18	0.27	0.19	0.08	2.17	0.23	0.21	0.07	2.17	0.32	0.19	0.12
2.24	0.26	0.19	0.09	2.23	0.25	0.22	0.07	2.23	0.27	0.19	0.12
2.30	0.27	0.19	0.09	2.30	0.27	0.23	0.07	2.30	0.28	0.19	0.12
2.36	0.29	0.19	0.09	2.36	0.28	0.23	0.08	2.36	0.28	0.19	0.12
2.43	0.31	0.19	0.09	2.42	0.29	0.24	0.08	2.42	0.26	0.19	0.12
2.49	0.30	0.19	0.10	2.48	0.30	0.24	0.08	2.48	0.24	0.19	0.12
2.55	0.33	0.19	0.10	2.54	0.28	0.24	0.09	2.54	0.23	0.19	0.12
2.61	0.36	0.19	0.10	2.61	0.28	0.25	0.09	2.61	0.27	0.19	0.12
2.67	0.39	0.20	0.11	2.67	0.29	0.25	0.09	2.67	0.22	0.19	0.12
2.74	0.47	0.20	0.12	2.73	0.32	0.26	0.09	2.73	0.21	0.19	0.12
2.80	0.59	0.21	0.14	2.80	0.31	0.26	0.10	2.79	0.24	0.19	0.12
2.86	0.77	0.22	0.16	2.86	0.30	0.27	0.10	2.85	0.25	0.20	0.12
2.92	1.04	0.24	0.19	2.92	0.30	0.28	0.10	2.92	0.22	0.19	0.12
2.98	1.33	0.28	0.22	2.98	0.32	0.28	0.10	2.98	0.23	0.20	0.12
3.05	1.65	0.33	0.27	3.05	0.32	0.28	0.11	3.04	0.22	0.19	0.12
3.11	1.87	0.42	0.31	3.11	0.33	0.29	0.11	3.10	0.21	0.19	0.12
3.17	2.09	0.50	0.35	3.17	0.33	0.29	0.11	3.16	0.24	0.19	0.12
3.23	2.16	0.57	0.38	3.23	0.35	0.29	0.11	3.23	0.25	0.19	0.12
3.29	2.17	0.61	0.41	3.30	0.36	0.30	0.12	3.29	0.22	0.19	0.12
3.36	2.11	0.61	0.43	3.36	0.36	0.31	0.12	3.35	0.22	0.19	0.12
3.42	2.04	0.60	0.44	3.42	0.35	0.32	0.12	3.41	0.22	0.19	0.12
3.48	1.89	0.60	0.45	3.48	0.37	0.32	0.13	3.47	0.22	0.19	0.12
3.54	1.74	0.59	0.45	3.54	0.35	0.32	0.13	3.54	0.24	0.19	0.12
3.61	1.59	0.60	0.45	3.61	0.39	0.33	0.13	3.60	0.23	0.18	0.12
3.67	1.45	0.61	0.45	3.67	0.40	0.34	0.13	3.66	0.23	0.18	0.12
3.73	1.31	0.60	0.45	3.73	0.42	0.34	0.14	3.72	0.23	0.19	0.13

3.79	1.19	0.59	0.44	3.79	0.41	0.35	0.14	3.78	0.23	0.18	0.13
3.85	1.06	0.58	0.44	3.85	0.41	0.36	0.14	3.85	0.23	0.18	0.13
3.92	0.99	0.55	0.43	3.92	0.41	0.36	0.15	3.91	0.21	0.18	0.13
3.98	0.96	0.53	0.43	3.98	0.43	0.36	0.15	3.97	0.25	0.18	0.13
4.04	0.93	0.51	0.43	4.04	0.44	0.36	0.15	4.03	0.22	0.18	0.13
4.10	0.94	0.49	0.43	4.10	0.44	0.37	0.16	4.09	0.26	0.18	0.13
4.17	0.93	0.47	0.44	4.17	0.43	0.37	0.16	4.16	0.27	0.18	0.13
4.23	0.94	0.47	0.44	4.23	0.44	0.38	0.16	4.22	0.24	0.18	0.13
4.29	0.94	0.45	0.44	4.29	0.43	0.38	0.16	4.28	0.26	0.18	0.13
4.35	0.96	0.45	0.44	4.35	0.43	0.38	0.17	4.34	0.26	0.19	0.14
4.41	0.95	0.45	0.44	4.41	0.44	0.39	0.17	4.40	0.26	0.19	0.14
4.48	0.93	0.45	0.44	4.48	0.43	0.39	0.17	4.47	0.26	0.19	0.14
4.54	0.91	0.45	0.44	4.54	0.44	0.38	0.17	4.53	0.27	0.19	0.14
4.60	0.90	0.45	0.44	4.60	0.43	0.39	0.18	4.59	0.29	0.20	0.15
4.66	0.87	0.45	0.44	4.66	0.44	0.39	0.18	4.65	0.29	0.20	0.15
4.73	0.87	0.45	0.44	4.72	0.43	0.39	0.18	4.71	0.29	0.20	0.15
4.79	0.86	0.46	0.44	4.79	0.44	0.39	0.19	4.78	0.30	0.20	0.15
4.85	0.83	0.46	0.44	4.85	0.43	0.39	0.19	4.84	0.31	0.20	0.15
4.91	0.81	0.47	0.44	4.91	0.42	0.39	0.19	4.90	0.33	0.21	0.15
4.97	0.79	0.47	0.44	4.97	0.41	0.39	0.19	4.96	0.31	0.21	0.16
5.04	0.77	0.48	0.44	5.04	0.44	0.39	0.19	5.02	0.32	0.22	0.16
5.10	0.78	0.48	0.44	5.10	0.41	0.39	0.20	5.09	0.32	0.22	0.16
5.16	0.75	0.49	0.44	5.16	0.44	0.39	0.20	5.15	0.31	0.22	0.16
5.22	0.74	0.49	0.44	5.22	0.44	0.39	0.20	5.21	0.34	0.24	0.16
5.28	0.74	0.50	0.44	5.28	0.44	0.39	0.20	5.27	0.32	0.24	0.16
5.35	0.75	0.51	0.44	5.35	0.43	0.40	0.21	5.34	0.33	0.24	0.17
5.41	0.72	0.51	0.44	5.41	0.43	0.40	0.21	5.40	0.32	0.25	0.17
5.47	0.70	0.52	0.44	5.47	0.43	0.40	0.21	5.46	0.33	0.25	0.17
5.53	0.71	0.52	0.44	5.53	0.43	0.40	0.21	5.52	0.34	0.26	0.18
5.59	0.71	0.52	0.44	5.60	0.45	0.40	0.21	5.58	0.33	0.26	0.18
5.66	0.69	0.53	0.44	5.66	0.44	0.41	0.22	5.65	0.34	0.27	0.18
5.72	0.69	0.54	0.44	5.72	0.46	0.41	0.22	5.71	0.32	0.27	0.18
5.78	0.68	0.54	0.44	5.78	0.44	0.41	0.22	5.77	0.33	0.27	0.19
5.84	0.67	0.54	0.44	5.84	0.43	0.41	0.22	5.83	0.35	0.26	0.19
5.91	0.66	0.54	0.44	5.91	0.44	0.41	0.22	5.89	0.32	0.26	0.19
5.97	0.67	0.55	0.44	5.97	0.44	0.41	0.22	5.96	0.32	0.25	0.19
6.03	0.67	0.55	0.44	6.03	0.45	0.42	0.22	6.02	0.34	0.25	0.19
6.09	0.66	0.55	0.44	6.09	0.45	0.42	0.22	6.08	0.35	0.24	0.19
6.15	0.63	0.56	0.44	6.15	0.46	0.42	0.23	6.14	0.33	0.24	0.19
6.22	0.64	0.54	0.44	6.22	0.45	0.42	0.23	6.20	0.32	0.24	0.19
6.28	0.65	0.55	0.44	6.28	0.44	0.42	0.23	6.27	0.32	0.23	0.19
6.34	0.63	0.55	0.44	6.34	0.44	0.42	0.23	6.33	0.35	0.23	0.19
6.40	0.64	0.56	0.44	6.40	0.46	0.43	0.23	6.39	0.35	0.22	0.19
6.47	0.63	0.55	0.44	6.47	0.46	0.44	0.24	6.45	0.33	0.22	0.19
6.53	0.62	0.55	0.44	6.53	0.44	0.43	0.24	6.52	0.33	0.22	0.19
6.59	0.62	0.55	0.44	6.59	0.46	0.44	0.24	6.58	0.33	0.22	0.19

6.65	0.61	0.56	0.44	6.65	0.46	0.43	0.24	6.64	0.33	0.22	0.19
6.72	0.61	0.56	0.43	6.71	0.44	0.44	0.25	6.70	0.35	0.21	0.19
6.78	0.61	0.57	0.43	6.78	0.47	0.44	0.25	6.76	0.34	0.22	0.20
6.84	0.60	0.56	0.43	6.84	0.47	0.44	0.25	6.83	0.33	0.22	0.20
6.90	0.61	0.57	0.43	6.90	0.48	0.45	0.25	6.89	0.33	0.22	0.20
6.96	0.61	0.57	0.43	6.96	0.47	0.45	0.25	6.95	0.32	0.22	0.20
7.03	0.58	0.57	0.43	7.02	0.47	0.45	0.26	7.01	0.33	0.22	0.20
7.09	0.59	0.57	0.43	7.09	0.49	0.46	0.26	7.08	0.33	0.22	0.20
7.15	0.60	0.57	0.43	7.15	0.49	0.46	0.26	7.14	0.32	0.22	0.20
7.21	0.60	0.57	0.43	7.21	0.49	0.46	0.26	7.20	0.33	0.22	0.20
7.27	0.60	0.58	0.43	7.27	0.50	0.46	0.26	7.26	0.31	0.22	0.20
7.34	0.58	0.58	0.43	7.34	0.48	0.47	0.26	7.32	0.30	0.22	0.20
7.40	0.57	0.58	0.43	7.40	0.47	0.47	0.27	7.39	0.31	0.22	0.20
7.46	0.57	0.58	0.43	7.46	0.49	0.47	0.27	7.45	0.31	0.23	0.20
7.52	0.56	0.58	0.43	7.52	0.49	0.47	0.27	7.51	0.32	0.23	0.20
7.59	0.57	0.58	0.43	7.59	0.50	0.47	0.27	7.57	0.30	0.23	0.20
7.65	0.57	0.58	0.43	7.65	0.50	0.48	0.27	7.63	0.30	0.22	0.20
7.71	0.56	0.58	0.43	7.71	0.49	0.48	0.28	7.70	0.31	0.23	0.20
7.77	0.57	0.58	0.43	7.77	0.49	0.48	0.28	7.76	0.31	0.23	0.20
7.83	0.57	0.58	0.43	7.84	0.51	0.48	0.28	7.82	0.30	0.23	0.21
7.90	0.57	0.59	0.43	7.90	0.52	0.48	0.28	7.88	0.32	0.23	0.21
7.96	0.56	0.59	0.43	7.96	0.52	0.48	0.28	7.94	0.32	0.23	0.21
8.02	0.56	0.59	0.43	8.02	0.51	0.48	0.28	8.01	0.32	0.23	0.21
8.08	0.55	0.59	0.43	8.08	0.50	0.48	0.28	8.07	0.28	0.23	0.21
8.14	0.57	0.59	0.43	8.15	0.54	0.49	0.28	8.13	0.31	0.23	0.21
8.21	0.56	0.59	0.43	8.21	0.52	0.49	0.28	8.19	0.31	0.23	0.22
8.27	0.55	0.59	0.43	8.27	0.51	0.49	0.28	8.25	0.31	0.23	0.22
8.33	0.54	0.59	0.43	8.33	0.51	0.50	0.29	8.32	0.32	0.23	0.22
8.39	0.55	0.60	0.43	8.39	0.51	0.50	0.29	8.38	0.29	0.23	0.22
8.46	0.55	0.60	0.43	8.46	0.52	0.50	0.29	8.44	0.31	0.23	0.22
8.52	0.53	0.60	0.44	8.52	0.50	0.50	0.29	8.50	0.33	0.24	0.22
8.58	0.54	0.60	0.44	8.58	0.53	0.50	0.29	8.56	0.31	0.24	0.22
8.64	0.55	0.60	0.44	8.64	0.51	0.49	0.30	8.63	0.30	0.24	0.22
8.70	0.55	0.60	0.44	8.71	0.51	0.49	0.30	8.69	0.30	0.24	0.22
8.77	0.54	0.61	0.44	8.77	0.50	0.50	0.30	8.75	0.32	0.24	0.22
8.83	0.54	0.61	0.44	8.83	0.52	0.50	0.30	8.81	0.33	0.24	0.22
8.89	0.53	0.60	0.44	8.89	0.50	0.50	0.30	8.88	0.32	0.25	0.22
8.96	0.53	0.60	0.44	8.95	0.50	0.50	0.30	8.94	0.32	0.25	0.22
9.02	0.51	0.60	0.44	9.02	0.50	0.51	0.30	9.00	0.33	0.25	0.22
9.08	0.54	0.61	0.44	9.08	0.51	0.51	0.31	9.06	0.31	0.25	0.22
9.14	0.55	0.61	0.44	9.14	0.51	0.52	0.31	9.12	0.34	0.26	0.22
9.21	0.53	0.61	0.44	9.20	0.50	0.52	0.31	9.19	0.35	0.27	0.23
9.27	0.54	0.61	0.44	9.26	0.50	0.52	0.31	9.25	0.36	0.28	0.23
9.33	0.52	0.61	0.44	9.33	0.51	0.52	0.31	9.31	0.37	0.29	0.23
9.39	0.53	0.62	0.44	9.39	0.51	0.52	0.31	9.37	0.39	0.30	0.23
9.45	0.53	0.62	0.44	9.45	0.49	0.52	0.31	9.43	0.44	0.31	0.23

9.52	0.52	0.62	0.44	9.51	0.50	0.53	0.31	9.50	0.44	0.32	0.23
9.58	0.52	0.62	0.44	9.58	0.50	0.53	0.31	9.56	0.43	0.34	0.23
9.64	0.52	0.62	0.44	9.64	0.50	0.53	0.32	9.62	0.40	0.35	0.24
9.70	0.53	0.62	0.44	9.70	0.50	0.52	0.32	9.68	0.41	0.36	0.25
9.76	0.52	0.62	0.44	9.76	0.52	0.53	0.32	9.74	0.40	0.36	0.25
9.83	0.51	0.63	0.44	9.82	0.49	0.53	0.32	9.81	0.38	0.36	0.25
9.89	0.50	0.62	0.44	9.89	0.50	0.53	0.32	9.87	0.38	0.37	0.25
9.95	0.53	0.62	0.44	9.95	0.49	0.53	0.32	9.93	0.39	0.37	0.25
10.02	0.51	0.62	0.44	10.01	0.49	0.52	0.32	10.00	0.39	0.36	0.26
10.08	0.49	0.62	0.44	10.07	0.49	0.54	0.32	10.06	0.39	0.37	0.26
10.14	0.50	0.62	0.45	10.13	0.50	0.55	0.32	10.12	0.40	0.37	0.26
10.20	0.49	0.62	0.45	10.20	0.49	0.55	0.32	10.18	0.39	0.37	0.27
10.26	0.48	0.62	0.45	10.26	0.48	0.55	0.32	10.24	0.39	0.36	0.27
10.33	0.48	0.61	0.45	10.32	0.49	0.55	0.32	10.31	0.39	0.36	0.27
10.39	0.45	0.61	0.44	10.38	0.47	0.55	0.32	10.37	0.38	0.36	0.27
10.45	0.46	0.61	0.44	10.45	0.47	0.55	0.32	10.43	0.34	0.36	0.27
10.51	0.43	0.61	0.44	10.51	0.42	0.55	0.33	10.49	0.32	0.35	0.27
10.57	0.45	0.60	0.44	10.57	0.44	0.55	0.33	10.55	0.32	0.34	0.27
10.64	0.43	0.60	0.44	10.63	0.45	0.55	0.33	10.62	0.33	0.33	0.27
10.70	0.44	0.60	0.44	10.69	0.42	0.55	0.33	10.68	0.27	0.32	0.27
10.76	0.41	0.60	0.44	10.76	0.40	0.54	0.33	10.74	0.29	0.32	0.26
10.82	0.43	0.59	0.44	10.82	0.39	0.55	0.33	10.80	0.32	0.32	0.26
10.89	0.39	0.59	0.44	10.88	0.39	0.54	0.33	10.87	0.29	0.32	0.26
10.95	0.36	0.58	0.44	10.94	0.38	0.54	0.32	10.93	0.29	0.27	0.26
11.01	0.36	0.57	0.44	11.00	0.36	0.53	0.32	10.99	0.27	0.26	0.25
11.07	0.33	0.57	0.44	11.07	0.37	0.53	0.32	11.06	0.19	0.25	0.25
11.13	0.33	0.56	0.44	11.13	0.34	0.53	0.32	11.12	0.12	0.23	0.24
11.20	0.30	0.55	0.44	11.19	0.35	0.52	0.32	11.18	0.14	0.22	0.24
11.26	0.29	0.53	0.43	11.25	0.30	0.52	0.32	11.24	0.17	0.21	0.23
11.32	0.26	0.53	0.43	11.32	0.30	0.51	0.32	11.31	0.17	0.19	0.23
11.38	0.24	0.52	0.43	11.38	0.30	0.51	0.32	11.37	0.15	0.19	0.23
11.44	0.25	0.51	0.43	11.44	0.31	0.50	0.32	11.43	0.15	0.17	0.23
11.51	0.21	0.49	0.42	11.50	0.28	0.50	0.31	11.49	0.20	0.17	0.22
11.57	0.22	0.49	0.42	11.56	0.26	0.50	0.31	11.55	0.17	0.16	0.22
11.63	0.21	0.48	0.42	11.63	0.25	0.49	0.31	11.62	0.17	0.15	0.21
11.69	0.18	0.46	0.42	11.69	0.24	0.49	0.31	11.68	0.15	0.15	0.21
11.75	0.17	0.45	0.41	11.75	0.25	0.48	0.31	11.74	0.13	0.14	0.21
11.82	0.16	0.44	0.41	11.81	0.26	0.49	0.31	11.80	0.13	0.14	0.21
11.88	0.15	0.44	0.41	11.87	0.23	0.48	0.30	11.87	0.13	0.13	0.20
11.94	0.13	0.43	0.41	11.94	0.21	0.48	0.30	11.93	0.12	0.13	0.20
12.00	0.12	0.42	0.40	12.00	0.23	0.47	0.30	11.99	0.13	0.13	0.20
12.06	0.14	0.41	0.40	12.06	0.21	0.47	0.30	12.05	0.11	0.12	0.20
12.13	0.12	0.41	0.40	12.12	0.20	0.47	0.30	12.11	0.09	0.13	0.20
12.19	0.09	0.40	0.40	12.18	0.20	0.47	0.30	12.18	0.10	0.13	0.20
12.25	0.09	0.39	0.40	12.25	0.19	0.47	0.29	12.24	0.10	0.12	0.19
12.31	0.10	0.39	0.39	12.31	0.21	0.46	0.29	12.30	0.13	0.12	0.19

12.37	0.10	0.38	0.39	12.37	0.19	0.47	0.29	12.36	0.13	0.13	0.19
12.44	0.09	0.38	0.39	12.43	0.17	0.47	0.29	12.42	0.10	0.12	0.19
12.50	0.09	0.38	0.39	12.49	0.16	0.46	0.29	12.49	0.12	0.12	0.19
12.56	0.07	0.37	0.38	12.56	0.18	0.47	0.29	12.55	0.11	0.12	0.19
12.62	0.06	0.36	0.38	12.62	0.17	0.46	0.29	12.61	0.09	0.13	0.18
12.68	0.08	0.36	0.38	12.68	0.14	0.47	0.28	12.67	0.08	0.12	0.18
12.75	0.07	0.36	0.38	12.74	0.15	0.46	0.28	12.73	0.11	0.12	0.18
12.81	0.06	0.35	0.38	12.81	0.14	0.46	0.28	12.80	0.10	0.13	0.18
12.87	0.05	0.35	0.37	12.87	0.13	0.46	0.28	12.86	0.12	0.12	0.18
12.93	0.04	0.34	0.37	12.93	0.16	0.46	0.28	12.92	0.07	0.12	0.18
13.00	0.06	0.35	0.37	12.99	0.13	0.46	0.28	12.98	0.09	0.12	0.17
13.06	0.06	0.34	0.37	13.05	0.11	0.46	0.28	13.04	0.09	0.13	0.17
13.12	0.01	0.34	0.37	13.12	0.13	0.46	0.27	13.11	0.09	0.13	0.17
13.18	0.04	0.34	0.36	13.18	0.13	0.47	0.27	13.17	0.07	0.13	0.17
13.24	0.05	0.33	0.36	13.24	0.13	0.46	0.27	13.23	0.05	0.12	0.17
13.31	0.02	0.33	0.36	13.30	0.09	0.47	0.27	13.29	0.05	0.13	0.17
13.37	0.02	0.33	0.36	13.37	0.14	0.47	0.27	13.35	0.05	0.12	0.16
13.43	0.02	0.33	0.36	13.43	0.11	0.47	0.27	13.42	0.04	0.12	0.16
13.49	0.03	0.33	0.35	13.50	0.11	0.47	0.27	13.48	0.05	0.12	0.16
13.55	0.04	0.33	0.35	13.56	0.12	0.47	0.26	13.54	0.03	0.12	0.16
13.62	-0.01	0.33	0.35	13.63	0.10	0.47	0.26	13.60	0.04	0.12	0.16
13.68	-0.03	0.32	0.35	13.69	0.09	0.48	0.26	13.66	0.04	0.12	0.16
13.74	-0.03	0.32	0.35	13.76	0.09	0.48	0.26	13.73	0.01	0.12	0.16
13.80	-0.05	0.32	0.34	13.80	0.11	0.45	0.27	13.79	-0.01	0.12	0.16
13.87	-0.02	0.30	0.34	13.86	0.08	0.45	0.27	13.85	0.03	0.12	0.15
13.93	-0.05	0.31	0.34	13.93	0.12	0.45	0.27	13.91	0.03	0.12	0.15
13.99	-0.08	0.30	0.34	13.99	0.07	0.46	0.26	13.97	0.04	0.12	0.15
14.05	-0.09	0.29	0.33	14.05	0.10	0.46	0.26	14.04	0.04	0.12	0.15
14.12	-0.08	0.29	0.33	14.11	0.09	0.46	0.26	14.10	-0.03	0.12	0.15
14.18	-0.10	0.29	0.33	14.18	0.10	0.39	0.26	14.16	0.04	0.13	0.15
14.24	-0.08	0.29	0.33	14.24	0.08	0.39	0.26	14.22	0.04	0.13	0.14
14.30	-0.08	0.29	0.32	14.30	0.10	0.40	0.26	14.29	0.04	0.13	0.14
14.36	-0.05	0.29	0.32	14.37	0.06	0.41	0.25	14.35	0.00	0.12	0.14

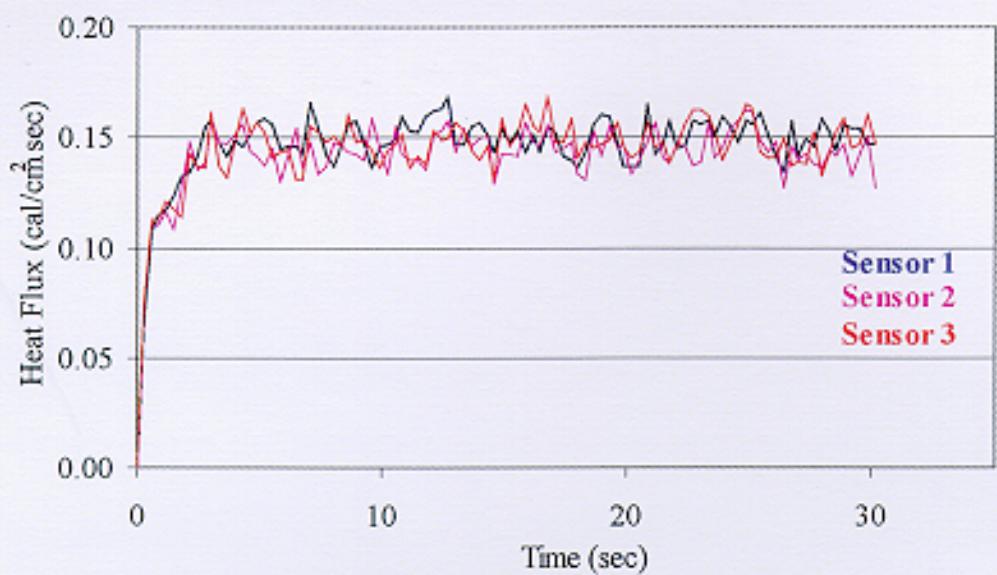
**Table A13: Heat Flux Results for 2.00 cal/cm<sup>2</sup>.sec TPP Covered Exposure.**

Flame Retardant Cotton		Nomex		Wool	
Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)	Time (sec)	Heat Flux (cal/cm <sup>2</sup> .sec)
0.04	0.00	0.04	0.01	0.04	0.02
0.12	0.02	0.12	0.02	0.12	0.02

0.20	-0.02	0.20	0.09	0.20	-0.01
0.27	0.09	0.27	-0.01	0.27	0.07
0.34	0.03	0.34	0.05	0.35	-0.01
0.42	0.00	0.42	0.05	0.42	0.00
0.49	0.03	0.49	0.04	0.50	0.01
0.57	0.05	0.56	0.06	0.57	0.04
0.64	0.03	0.64	0.05	0.64	0.03
0.71	0.06	0.71	0.08	0.72	0.03
0.79	0.06	0.78	0.07	0.79	0.01
0.86	0.06	0.86	0.07	0.87	0.03
0.94	0.07	0.93	0.07	0.94	0.05
1.01	0.11	1.01	0.12	1.02	0.04
1.09	0.11	1.08	0.11	1.09	0.04
1.16	0.16	1.15	0.09	1.17	0.04
1.24	0.19	1.23	0.16	1.24	0.04
1.31	0.20	1.30	0.17	1.32	0.05
1.39	0.22	1.37	0.21	1.39	0.08
1.46	0.23	1.45	0.19	1.46	0.09
1.54	0.20	1.52	0.21	1.54	0.13
1.61	0.24	1.60	0.18	1.61	0.08
1.69	0.21	1.67	0.22	1.69	0.20
1.76	0.21	1.74	0.21	1.76	0.19
1.84	0.25	1.82	0.19	1.84	0.22
1.92	0.19	1.89	0.21	1.91	0.24
1.99	0.22	1.97	0.18	1.99	0.25
2.07	0.21	2.04	0.23	2.06	0.23
2.14	0.20	2.12	0.21	2.13	0.24
2.22	0.25	2.19	0.24	2.21	0.29
2.29	0.20	2.26	0.24	2.28	0.27
2.37	0.21	2.34	0.24	2.36	0.24
2.44	0.24	2.41	0.25	2.43	0.26
2.52	0.21	2.49	0.25	2.51	0.26
2.59	0.25	2.56	0.27	2.58	0.27
2.66	0.28	2.63	0.29	2.65	0.27
2.74	0.27	2.71	0.30	2.73	0.26
2.81	0.29	2.78	0.31	2.80	0.25
2.89	0.41	2.86	0.31	2.88	0.25
2.96	0.47	2.93	0.30	2.95	0.26
3.04	0.56	3.00	0.33	3.03	0.25
3.11	0.70	3.08	0.31	3.10	0.26
3.19	0.86	3.15	0.33	3.18	0.24
3.26	1.06	3.23	0.33	3.26	0.24
3.34	1.21	3.30	0.36	3.33	0.24
3.41	1.39	3.37	0.35	3.41	0.24
3.49	1.42	3.45	0.38	3.48	0.22

3.56	1.53	3.52	0.39	3.56	0.21
3.64	1.61	3.60	0.38	3.63	0.21
3.71	1.64	3.67	0.40	3.71	0.20
3.79	1.58	3.74	0.38	3.78	0.24
3.86	1.51	3.82	0.41	3.85	0.19
3.94	1.42	3.89	0.42	3.93	0.21
4.01	1.25	3.97	0.43	4.00	0.20
4.09	1.10	4.04	0.49	4.08	0.21
4.16	1.04	4.12	0.42	4.16	0.23
4.24	1.00	4.20	0.44	4.23	0.17
4.31	0.97	4.27	0.49	4.31	0.20
4.39	0.96	4.34	0.46	4.38	0.20
4.46	0.96	4.42	0.45	4.46	0.19
4.54	0.95	4.49	0.48	4.53	0.22
4.62	0.95	4.57	0.48	4.60	0.17
4.69	0.96	4.64	0.47	4.68	0.23
4.77	0.95	4.72	0.47	4.75	0.19
4.84	0.94	4.79	0.45	4.83	0.22
4.92	0.90	4.87	0.45	4.90	0.23
4.99	0.91	4.94	0.48	4.98	0.21
5.07	0.88	5.01	0.48	5.05	0.24
5.14	0.86	5.09	0.45	5.13	0.21
5.22	0.84	5.16	0.49	5.20	0.23
5.29	0.84	5.24	0.46	5.28	0.27
5.37	0.83	5.31	0.46	5.35	0.26
5.44	0.81	5.39	0.48	5.43	0.25
5.51	0.81	5.46	0.46	5.50	0.26
5.59	0.81	5.54	0.48	5.57	0.28
5.66	0.77	5.61	0.47	5.65	0.28
5.74	0.78	5.69	0.44	5.72	0.29
5.81	0.79	5.76	0.49	5.80	0.29
5.89	0.77	5.83	0.48	5.88	0.30
5.96	0.77	5.91	0.44	5.95	0.32
6.04	0.76	5.98	0.47	6.03	0.32
6.11	0.76	6.06	0.50	6.10	0.30
6.19	0.75	6.13	0.44	6.17	0.31
6.26	0.75	6.20	0.49	6.25	0.33
6.34	0.73	6.28	0.48	6.32	0.33
6.41	0.72	6.35	0.47	6.40	0.32
6.49	0.73	6.43	0.48	6.47	0.31
6.56	0.73	6.50	0.48	6.55	0.33
6.64	0.72	6.57	0.46	6.62	0.33
6.71	0.70	6.65	0.49	6.70	0.33
6.78	0.71	6.72	0.51	6.77	0.32
6.86	0.70	6.80	0.49	6.85	0.33

6.93	0.68	6.87	0.48	6.92	0.31
7.01	0.69	6.95	0.50	7.00	0.33
7.08	0.68	7.02	0.46	7.07	0.34
7.16	0.67	7.09	0.51	7.14	0.33
7.24	0.70	7.17	0.50	7.22	0.32
7.31	0.63	7.24	0.50	7.29	0.32
7.39	0.66	7.32	0.50	7.37	0.35
7.47	0.65	7.39	0.50	7.44	0.34
7.54	0.67	7.46	0.52	7.52	0.31
7.62	0.62	7.54	0.53	7.59	0.33
7.69	0.64	7.61	0.52	7.67	0.34
7.77	0.65	7.69	0.52	7.74	0.32
7.84	0.63	7.76	0.51	7.82	0.32
7.92	0.62	7.83	0.53	7.89	0.32
7.99	0.64	7.91	0.54	7.96	0.35
8.06	0.64	7.98	0.55	8.04	0.32
8.14	0.65	8.06	0.54	8.11	0.34
8.21	0.63	8.13	0.53	8.19	0.35
8.29	0.61	8.21	0.53	8.26	0.34
8.36	0.62	8.28	0.54	8.34	0.34
8.44	0.63	8.36	0.57	8.41	0.34
8.51	0.63	8.43	0.53	8.49	0.34
8.58	0.62	8.50	0.56	8.56	0.35
8.66	0.61	8.58	0.55	8.64	0.35
8.73	0.63	8.65	0.56	8.71	0.35
8.81	0.62	8.73	0.55	8.78	0.34
8.88	0.58	8.80	0.54	8.86	0.35
8.96	0.61	8.88	0.58	8.93	0.33
9.03	0.63	8.95	0.52	9.01	0.35
9.11	0.62	9.03	0.56	9.08	0.35
9.18	0.61	9.10	0.57	9.16	0.36
9.26	0.57	9.17	0.55	9.23	0.36
9.33	0.60	9.25	0.58	9.31	0.35
9.41	0.61	9.32	0.56	9.38	0.38
9.48	0.58	9.40	0.55	9.46	0.38
9.56	0.57	9.47	0.57	9.53	0.37
9.63	0.61	9.55	0.56	9.61	0.44
9.71	0.58	9.62	0.57	9.68	0.45
9.78	0.59	9.69	0.55	9.76	0.45
9.86	0.59	9.77	0.57	9.83	0.43
9.93	0.60	9.84	0.54	9.91	0.46
9.99	0.60	9.92	0.59	9.95	0.54



**Figure A1: Insulated Copper Average of 4 Trials @ 0.14 cal/cm<sup>2</sup>sec Nude Exposure.**

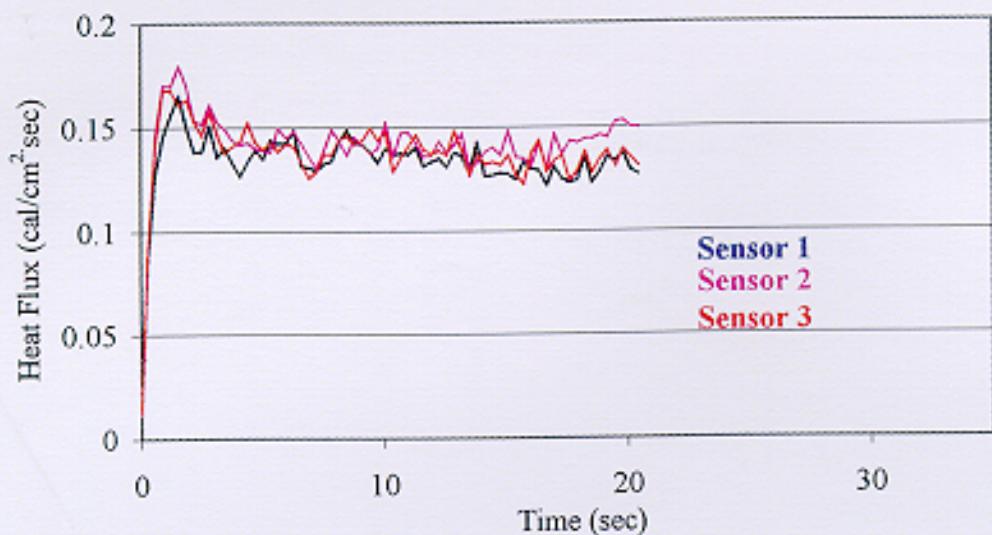


Figure A2: Embedded Thermocouple Average of 4 Trials @  $0.14 \text{ cal}/\text{cm}^2 \text{sec}$  Nude Exposure.

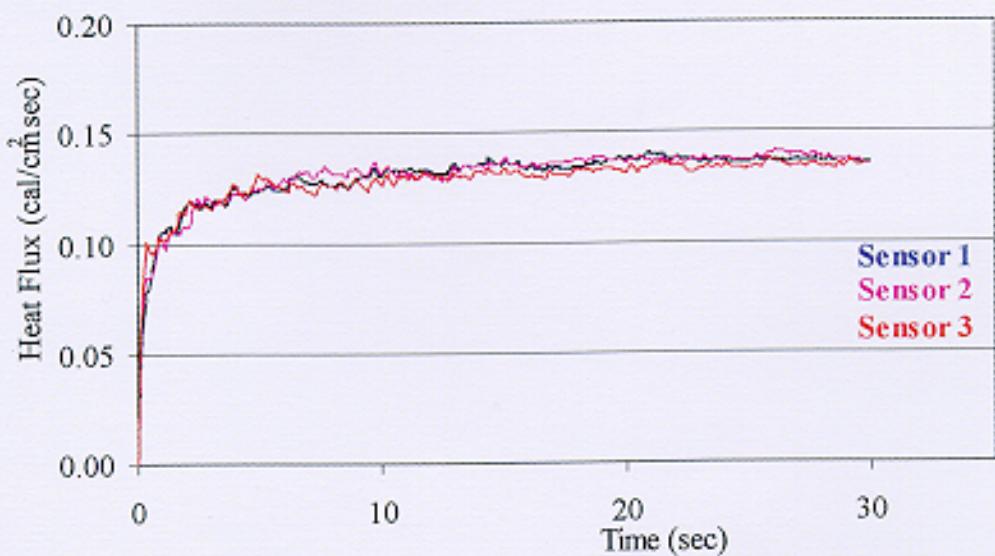


Figure A3: Surface Thermocouple Average of 4 Trials @  $0.14 \text{ cal}/\text{cm}^2 \text{sec}$  Nude Exposure.

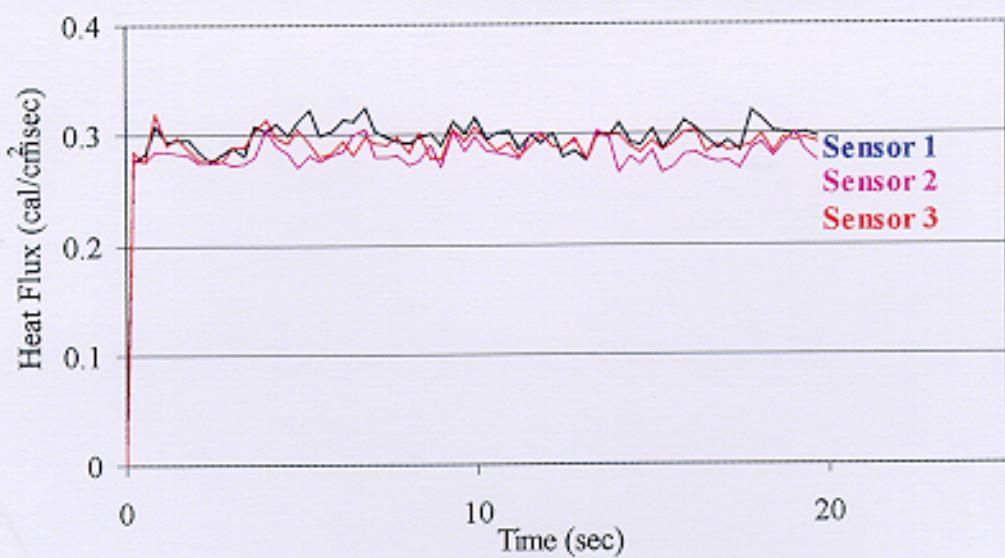


Figure A4: Insulated Copper Average of 4 Trials @  $0.30 \text{ cal}/\text{cm}^2\text{sec}$  Nude Exposure.

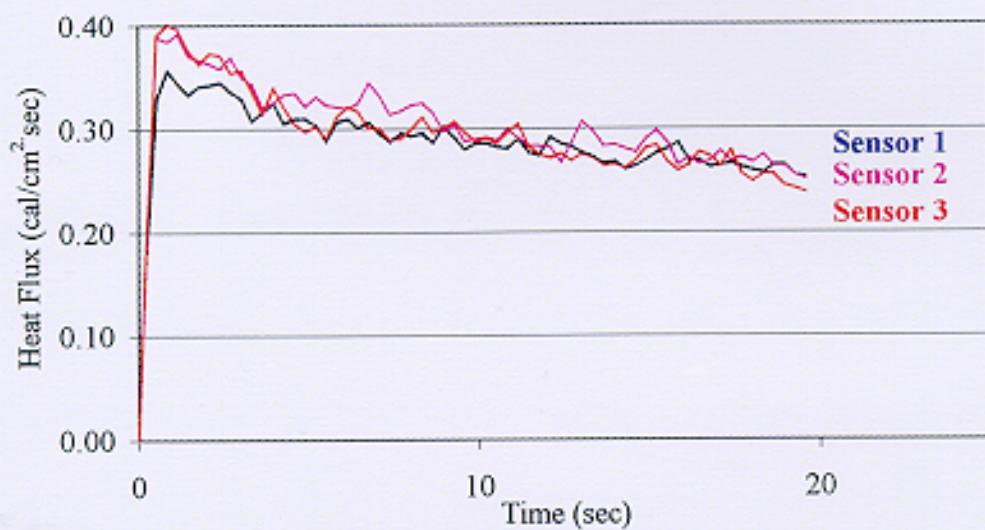


Figure A5: Embedded Thermocouple Average of 4 Trials @  $0.30 \text{ cal}/\text{cm}^2\text{sec}$  Nude Exposure.

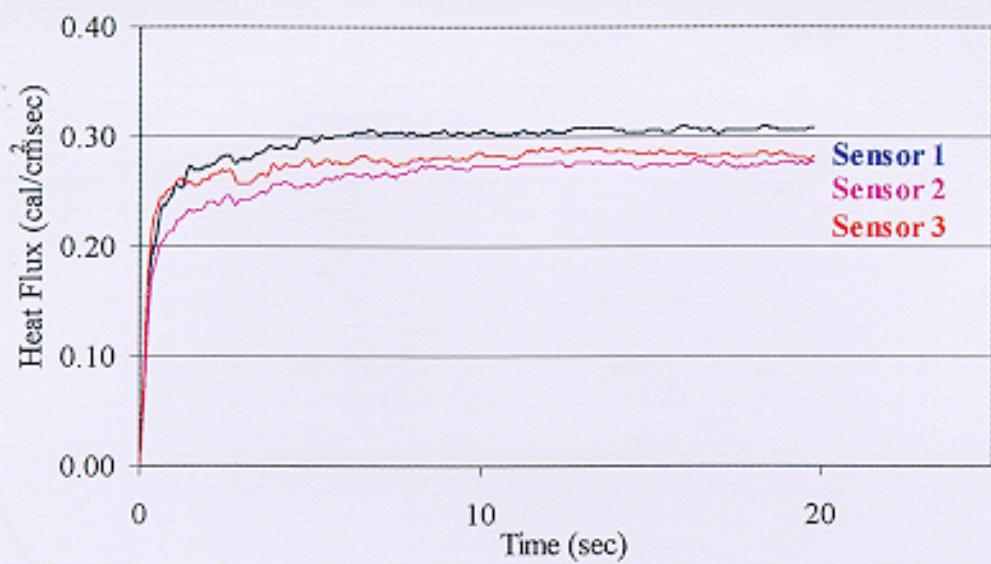


Figure A6.: Surface Thermocouple Average of 4 Trials @ 0.30 cal/cm<sup>2</sup>sec Nude Exposure.

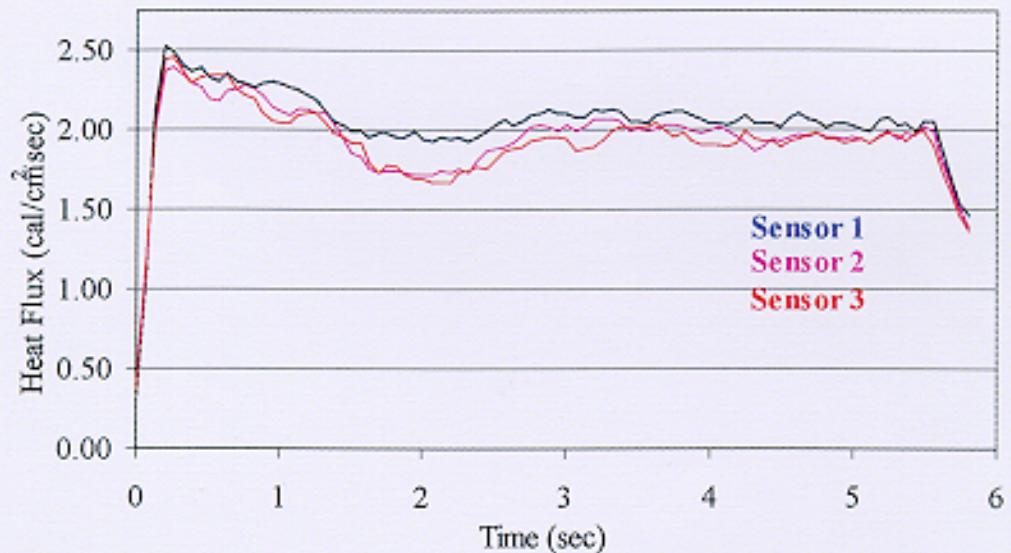


Figure A7.: Insulated Copper Average of 4 Trials @ 2.00 cal/cm<sup>2</sup>sec Nude Exposure.

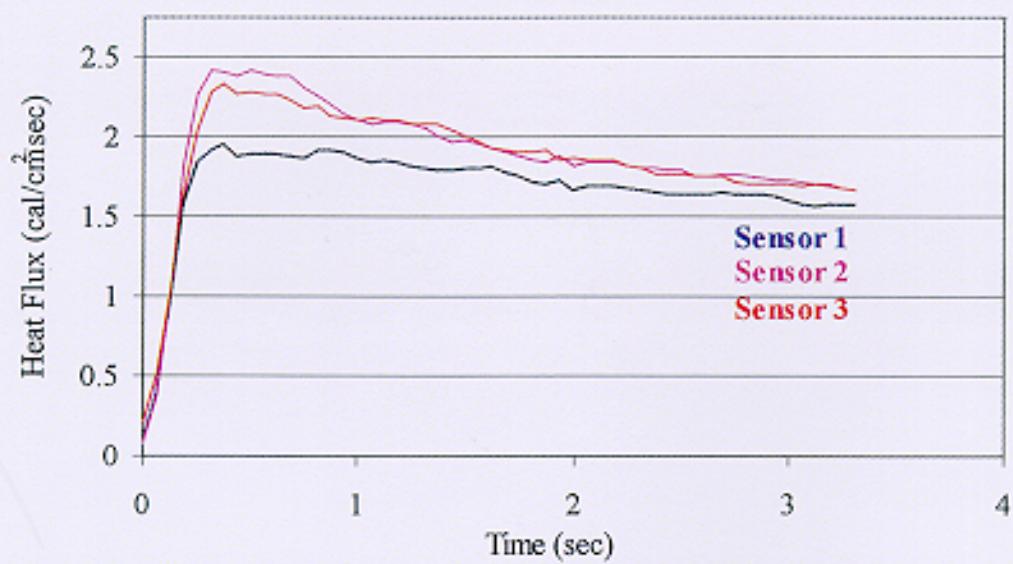


Figure A8: Embedded Thermocouple Average of 4 Trials @ 2.00  $\text{cal}/\text{cm}^2\text{sec}$  Nude Exposure.

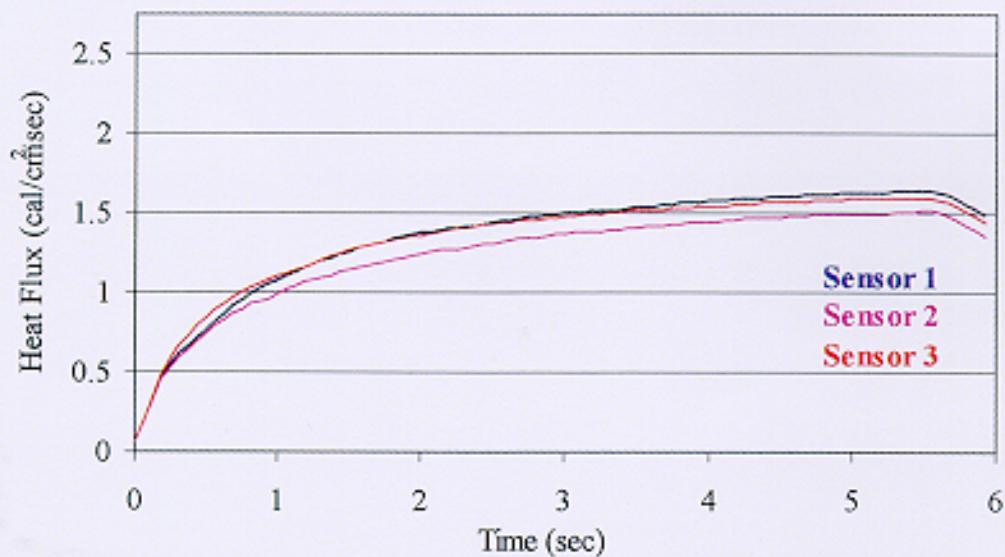


Figure A9: Surface Thermocouple Average of 4 Trials @ 2.00  $\text{cal}/\text{cm}^2\text{sec}$  Nude Exposure.

**Appendix B**

**Procedures Used for Burn Prediction**

A Fortran program was written to calculate the surface and interior temperature distribution in human skin and calculate a probable burn damage for the skin at selected depths. The program utilizes the same constants as a widely used model (Model B, Table B1), simply for a basis of comparison. The program outputs both a skin temperature history and a skin burn damage history at two points within the skin that are chosen by the user. The program then calculates a temperature distribution in human skin using a finite difference model.

The developed Fortran program was used to compute burn injury information for the sensors. This model can be manipulated to look at burns at different skin levels; however, for now, we are simply providing a method of comparison among sensors. Data taken from the TPP sensor was evaluated by this method and applied to the Stoll curve to provide validity to our burn model.

The following program assumes that skin is opaque and that circulatory effects are invariant during the period of exposure. This means that energy is transferred internally by conduction only, thus allowing the circulatory effects to be considered lumped with the thermal conductivity. The model then divides the skin into a series of iso-thermal nodes, each with an assigned thickness, thermal conductivity, and specific heat as seen in Table B1. The heat flux measured by the sensor is the boundary condition at the surface, and the back wall is assumed to be adiabatic [7].

**Table B1. Thermal Properties of Human Skin [7,8]**

Properties	Model A		Model B	
	Epidermis	Dermis	Epidermis	Dermis
Node depth (cm)	$80 \times 10^{-4}$	$2000 \times 10^{-4}$	$100 \times 10^{-4}$	$1250 \times 10^{-4}$
k (cal/cm <sup>sec</sup> °C)	$6.1 \times 10^{-4}$	$12.5 \times 10^{-4}$	$8.0 \times 10^{-4}$	$8.0 \times 10^{-4}$
$\rho$ (g/cm <sup>3</sup> )	1.2	1.2	1.2	1.2
C (cal/g °C)	0.86	0.77	0.77	0.77
$\alpha$ (cm <sup>2</sup> /sec)	$5.91 \times 10^{-4}$	$13.53 \times 10^{-4}$	$8.66 \times 10^{-4}$	$8.66 \times 10^{-4}$
$k\rho C$ (cal <sup>2</sup> /cm <sup>4</sup> °C <sup>2</sup> sec)	$6.30 \times 10^{-4}$	$11.55 \times 10^{-4}$	$7.39 \times 10^{-4}$	$7.39 \times 10^{-4}$

On the basis of the calculated surface heat flux, a multi-layer skin model can be solved for the skin temperatures using the Crank-Nicolson Implicit method. This method calculates a skin temperature distribution based on approximate node depths. From the skin temperature distribution, the following Arrhenius relation can determine the degree of thermal injury:

$$\frac{d\Omega}{d\theta} = Ce^{\frac{-\Delta E}{RT}}$$

Where:

C	=	Rate constant (1/sec)
$\Delta E$	=	Activation energy for tissue destruction (cal/mole)
R	=	Universal gas constant (cal/mole $^{\circ}$ K)
T	=	Absolute temperature at the basal layer at time t ( $^{\circ}$ K)

In the model, the burn injury parameter,  $\Omega$ , is determined for each node at each time step. This is done by evaluating the damage rate factor,  $d\Omega/d\theta$ , as a function of temperature through integration. The integral is known as the "Henriques Damage Integral." It is assumed that when  $\Omega \geq 1.0$  at a given skin depth, thermal destruction of collagen occurs resulting in irreversible skin damage [6]. Degree of burn is a function of the depth of skin destruction. Once the  $\Omega$  is calculated, the degree and time to 2<sup>nd</sup> and 3<sup>rd</sup> degree burn can be determined.

Stoll and Chianta, based on the work of Henriques, studied tissue damage and skin temperatures due to thermal radiation, open flame and conduction, and found that tissue damage occurs when the temperature remains above 44 °C. This was found to be true during the heating and cooling period. Stoll's work produced different coefficients for the "Henriques Damage Integral." A comparison of constants can be seen in Table B2 [6].

Data from Stoll's work is used in bench scale tests of protective fabrics to make estimates of the time it takes for second degree burn damage to begin to occur for a given exposure. A graph of this data is known as the Stoll curve, and is widely accepted as the criteria used to comparatively evaluate heat resistant fabrics [6].

**Table B2. Coefficients of the Arrhenius Equation [6].**

Source	Epidermis		Dermis	
	C (1/sec)	ΔE (cal/mole)	C (1/sec)	ΔE (cal/mole)
Henriques	$3.10 \times 10^{98}$	150,000	$3.10 \times 10^{129}$	150,000
Stoll	$1.11 \times 10^{125}$	194,000	$1.10 \times 10^{54}$	194,000

The thermal properties of human skin may be taken to be homogeneous to help simplify the calculations. This differs from Model A since the skin is actually heterogeneous. Dermal, epidermal and subcutaneous layers are not accounted for in this model. Additionally, blood perfusion and different water contents are not taken into account. The model is a Crank-Nicolson based model that takes into account small node spacing and varying time steps. However, the program does not account for radiative heat losses from human skin as is done in Model B.

The node spacing for the program is currently set at 0.004 inches. The burn damage is currently being calculated at nodes 2 (0.004", 0.01cm) and 13 (0.048", 0.1250cm), based on average human skin thicknesses. Differences are seen between different existing models, mainly in the location of the critical skin depths, and the physical properties attributed to human skin. Our model can be manipulated to look at burns at different skin levels; however, for now, we are simply providing a method of comparison among sensors. Data taken from the TPP sensor was evaluated by this method and applied to the Stoll curve, as to provide validity to our burn model.

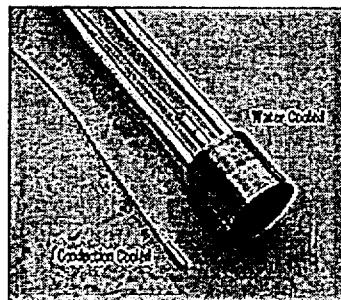
## **Appendix C**

### **Thermogage™ Water Cooled Sensor Specifications**

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## THERMOGAGE<sup>TM</sup>

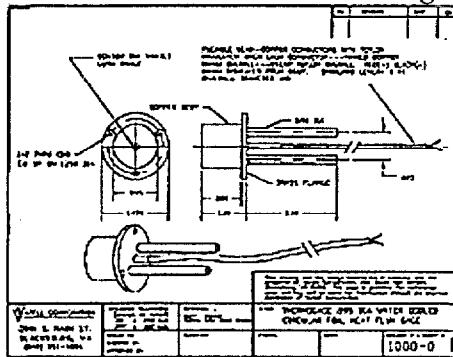


### 1000 Series, Water Cooled

#### ADVANTAGES

- High Sensitivity
- Continuous Cooling- Infinite Exposure Time
- Linear Output With Changes in Temperature
  - Rugged All Metal Construction
  - Wide Range of Sensor and Housing Combinations
- Guaranteed Quality- Warranted for 1 year

#### Standard Water Cooled Gauge

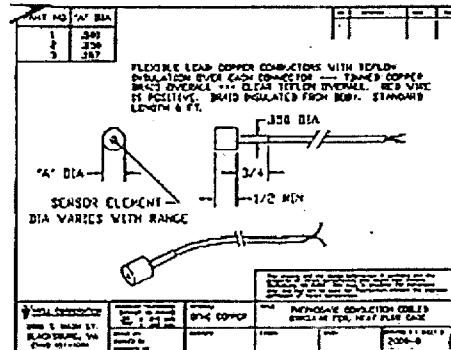


### 2000 Series, Conduction Cooled

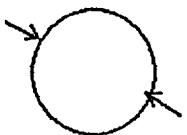
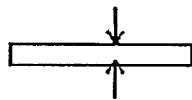
#### ADVANTAGES

- High Sensitivity
- External Coolant Unnecessary
- Linear Output With Changes in Temperature
  - Rugged All Metal Construction
  - Wide Range of Sensor and Housing Combinations
- Guaranteed Quality- Warranted for 1 year

#### Standard Conduction Cooled Gauge



### Sensor Specifications:

**Fig. 1****Fig. 2**

<b>Fig. 1</b>	<b>Foil Diameters:</b>	0.01" to 0.25"
<b>Fig. 2</b>	<b>Foil Thickness:</b>	0.0005" to 0.01"
	<b>Ranges for Full Scale Output:</b>	0 - 5 Watt / cm <sup>2</sup> to 0 - 5000 Watts / cm <sup>2</sup>
	<b>Response Time:</b>	Varies with range, can be as small as 1.5 milliseconds
	<b>Transducer Accuracy:</b>	±2%
	<b>Repeatability:</b>	1%
	<b>Sensitivity:</b>	varies with range

## Sensor Coating:

The factory applied base coat is colloidal graphite. It is selected for high emissivity, temperature stability, and flat spectral absorbency. Our method of application produces a quick drying, 0.0001 inch thick film of 0.82 emissivity. If your needs require, a higher emissivity black paint can be specified.

Most application requirements can be met by a gage that combines foil and housing designs from the 30 years of Thermogage experience. If your application requires a different sensor or housing, we can do that too! Our engineers work every day with customers to provide the best gages for their heat flux measurement needs.

## Operating Principles:

The transducer is a differential thermocouple pair measuring the temperature difference between the center and the circumference of a thin circular foil disk. The disk is bonded to a cylindrical heat sink. The standard foil is made of Constantan and the heat sink is copper. These materials produce an output which is directly proportional to the absorbed heat flux. These transducers can measure both radiative and convective heat flux, but not conductive heat flux. The gage is shown in cross section below.

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Barker, R.L., Hamouda, H., Shalev, I., Johnson, J., College of Textiles,  
North Carolina State University, Raleigh, NC

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The Center for Research on Textile Protection and Comfort (T-PACC) at North Carolina State University conducted a project which had, as its primary objective, the selection and evaluation of sensors that can be used to measure heat transferred through firefighter protective clothing materials, with the ultimate goal of applying this knowledge base to the development of rugged, and dependable laboratory benchtop and fire scene specific sensor technology. The purpose of this final report is to summarize the findings of this project and to recommend future directions in protection measuring heat flux sensor development.

## KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

firefighters; heat flux; heat sinks; measuring instruments; protective clothing;  
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